Stevens® Water Monitoring System, Inc.

The Hydra Probe® Soil Sensor

Comprehensive
Stevens Hydra Probe
Users Manual
92915 June 2008

Safety and Equipment Protection

WARNING!

ELECTRICAL POWER CAN RESULT IN DEATH, PERSONAL INJURY OR CAN CAUSE DAMAGE TO EQUIPMENT. If the instrument is driven by an external power source, disconnect the instrument from that power source before attempting any repairs.

WARNING!

BATTERIES ARE DANGEROUS. IF HANDLED IMPROPERLY, THEY CAN RESULT IN DEATH, PERSONAL INJURY OR CAN CAUSE DAMAGE TO EQUIPMENT. Batteries can be hazardous when misused, mishandled, or disposed of improperly. Batteries contain potential energy, even when partially discharged.

WARNING!

ELECTRICAL SHOCK CAN RESULT IN DEATH OR PERSONAL INJURY. Use extreme caution when handling cables, connectors, or terminals; they may yield hazardous currents if inadvertently brought into contact with conductive materials, including water and the human body.

CAUTION!

Be aware of protective measures against environmentally caused electric current surges. Read the Stevens Engineering Applications Note, *Surge Protection of Electronic Circuits*, part number 42147. In addition to the previous warnings and cautions, the following safety activities should be carefully observed.

Children and Adolescents.

NEVER give batteries to young people who may not be aware of the hazards associated with batteries and their improper use or disposal.

Jewelry, Watches, Metal Tags

To avoid severe burns, NEVER wear rings, necklaces, metal watch bands, bracelets, or metal identification tags near exposed battery terminals.

Heat, Fire

NEVER dispose of batteries in fire or locate them in excessively heated spaces. Observe the temperature limit listed in the instrument specifications.

Charging

NEVER charge "dry" cells or lithium batteries that are not designed to be charged.

NEVER charge rechargeable batteries at currents higher than recommended ratings.

NEVER recharge a frozen battery. Thaw it completely at room temperature before connecting charger.

Safety and Equipment Protection (Continued)

Unvented Container
NEVER store or charge batteries in a gas-tight container. Doing so may lead to pressure buildup and explosive concentrations of hydrogen.

Short Circuits
NEVER short circuit batteries. High current flow may cause internal battery heating and/or explosion.

Damaged Batteries
Personal injury may result from contact with hazardous materials from a damaged or open battery. NEVER attempt to open a battery enclosure. Wear appropriate protective clothing, and handle damaged batteries carefully.

Disposal
ALWAYS dispose of batteries in a responsible manner. Observe all applicable federal, state, and local regulations for disposal of the specific type of battery involved.

NOTICE
Stevens makes no claims as to the immunity of its equipment against lightning strikes, either direct or nearby.

The following statement is required by the Federal Communications Commission:

WARNING
This equipment generates, uses, and can radiate radio frequency energy and, if not installed in accordance with the instructions manual, may cause interference to radio communications. It has been tested and found to comply with the limits for a Class A computing device pursuant to Subpart J of Part 15 of FCC Rules, which are designed to provide reasonable protection against such interference when operated in a commercial environment. Operation of this equipment in a residential area is likely to cause interference in which case the user at his own expense will be required to take whatever measures may be required to correct the interference.

USER INFORMATION
Stevens makes no warranty as to the information furnished in these instructions and the reader assumes all risk in the use thereof. No liability is assumed for damages resulting from the use of these instructions. We reserve the right to make changes to products and/or publications without prior notice.

Comprehensive Stevens Hydra Probe II User's Manual

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1 Introduction

The Steven Hydra Probe Soil Sensor measures soil temperature, soil moisture and soil electrical conductivity and the complex dielectric permittivity. Designed for many years of service buried in soil, the Hydra Probe uses quality material in its construction. Marine grade stainless steel, ABS housing and a high grade epoxy potting protect the internal electrical component from the corrosive and reactive properties of soil. Most of the Hydra Probes installed more than a decade ago are still in service today.

The Hydra Probe is not only a practical measurement device it is also a scientific instrument. Trusted by farmers to maximize crop yields, using Hydra Probes in an irrigation system can prevent runoff that may be harmful to aquatic habitats, conserve water where it is scarce, and save money on pumping costs. Researchers can rely on the Hydra Probe to provide accurate and precise data for many years of service. The inter-sensor variability is very low, allowing direct comparison of data from multiple probes in a soil column or in a watershed.

The Hydra Probe bases it measurements on the physics and behavior of a reflected electromagnetic radio wave in soil to determine the dielectric constants. From the dielectric constants, the Hydra Probe can simultaneously measure soil moisture and electrical conductivity. The complex dielectric permittivity is related to the electrical capacitance and electrical conductivity. The Hydra Probe uses patented algorithms to convert the signal response of the standing radio wave into the dielectric constants and thus the soil moisture and soil electrical conductivity.

1.1 Applications

The US Department of Agriculture Soil Climate Analysis Network (SCAN) has depended on the Hydra Probe in hundreds of stations around the United States and Antarctica since the early 1990s. The Bureau of Reclamation's Agrimet Network, NOAA, and countless other mesonets and research watersheds around the world trust the measurements the Hydra Probe provides. Some of the applications include:

Agriculture
Viticulture
Research
Water Shed Modeling
Land Reclamation
Shrink/Swell Clays
Satellite Ground Truthing
Predicting Weather
Irrigation
Sports Turf
Phyto Soil Remediation
Evapotranspiration Studies
Land Slide Studies
Flood Forecasting
Wetland Delineation
Precision Agriculture

1.2 Temperature Corrections

The Hydra Probe's soil moisture and electrical conductivity measurements are temperature corrected providing temperature independent data year round.

1.3 Calibrations

The Hydra Probe has four calibrations that provide excellent performance in most mineral soils regardless of texture or organics. The calibrations are sand, silt, clay and loam. The loam soil calibration is the default calibration and is suitable for Silt Loams, Loam, Clay Loam, Silty Clay Loam, Sandy Clay Loam, Sandy Loam, and some medium textured clays.

1.4 Dielectric Constants

For research studies involving andisol pumas soil, wetland histasol soils or soil with extremely low bulk densities, the uncorrected and the temperature corrected dielectric constants are provided for custom calibrations.

1.5 Structural Components

There are three main structural components to the Hydra Probe. The marine grade stainless steel tine assembly is the wave guide. The tine assembly is the four metal rods that extend out of the base plate. Each tine is 45 mm long by 3 mm wide. The base plate is 25 mm in diameter. Electromagnetic waves at a radio frequency are transmitted and received by the center tine. The head or body of the probe contains the circuit boards, microprocessors, and all the other electrical components. The outer casing is ABS and the internal electronics are permanently potted with a rock-hard epoxy resin giving the probes a rugged construction. The cable has a direct burial casing and contains the power, ground, and data wires that are all soldered to the internal electronics.

1.6 Accuracy and Precision

The Hydra Probe provides accurate and precise measurements. Table 1.1 below shows the accuracy. For a detailed explanation of accuracy and precision and on the statistical evaluation of the Hydra Probe, see Appendix D.

Parameter	**Accuracy/Precision**
Temperature (C)	+/- 0.6 Degrees Celsius(From -10^{o} to 36^{o}C)
Soil Moisture wfv (m^3 m^{-3})	+/- 0.03 wfv (m^3 m^{-3}) Accuracy
Soil Moisture wfv (m^3 m^{-3})	+/- 0.003 wfv (m^3 m^{-3}) Precision
Electrical Conductivity (S/m) TUC*	+/- 0.0014 S/m or +/- 1%
Electrical Conductivity (S/m) TC**	+/- 0.0014 S/m or +/- 5%
Real/Imaginary Dielectric Constant TUC*	+/- 0.5 or +/- 1%
Real/Imaginary Dielectric Constant TC*	+/- 0.5 or +/- 5%

Table 1.1 Accuracy and Precision of the Hydra Probes' Parameters.
*TUC Temperature uncorrected full scale
**TC Temperature corrected from 0 to 35^{o} C

2 Configurations of the Hydra Probe

The Hydra Probe is available in three versions, differentiated by the manner that information is transferred.

- SDI-12
- RS-485
- Analog

The two digital versions (SDI-12 and RS-485) incorporate a microprocessor to process the information from the probe into useful data. This data is then transmitted digitally to a receiving instrument. SDI-12 and RS-485 are two different methods of transmitting digital data. In both versions there are electrical and protocol specifications that must be observed to ensure reliable data collection.

The Analog version requires an attached instrument to measure voltages. This information must then be processed to generate useful information. This can be done either in the attached instrument, such as a data logger, or at a central data processing facility.

All configurations provide the same measurement parameters with the same accuracy. The under lying physics behind how the Hydra Probe works, and the outer construction are also the same for each configuration. Table 2.1 provides a physical description of the Hydra Probe.

Feature	**Attribute**
Probe Length	12.4 cm (4.9 inches)
Diameter	4.2 cm (1.6 inches)
Sensing Volume* (Cylindrical measurement region)	Length 5.7 cm (2.2 inches) Diameter 3.0 cm (1.2 inches)
Weight	200g (cable 80 g/m)
Power Requirements	7 to 20 VDC (12 VDC is ideal)
Temperature Range	-10 to 65^{o} C
Storage Temperature Range	-40 to 70^{o} C

Table 2.1 Physical description of the Hydra Probe (All Versions)

The cylindrical measurement region or sensing volume is the soil that resides between the stainless steel tine assembly. The tine assembly is often referred to as the wave guide and probe signal averages the soil in the sensing volume.

2.1 Digital Probes

Digital probes offer some advantages over the Analog version. One is that post-processing of the data is not required. Another is that the data is not affected by the length of the cable. Analog probes, since their information is delivered as voltage, should only be used with relatively short cables, on the order of 8 meters (25 feet). Digital cables can be much longer. SDI-12 cables can be up to 50 meters long (150 feet), and RS-485 cables can be up to 1000 meters (3000 feet). Digital probes can also be used with short cables without any trouble. Some installations use cables that are less than a meter (three feet) long.

2.1.1 Addressing & Programming

The digital versions of the Hydra Probe (the SDI-12 and RS-485 versions) can be connected in parallel so that multiple probes can be connected to a single communications port of a data logger or other device. When multiple probes are connected this way, each probe must be assigned a unique address ***before they are installed***. The methods used for both probes are similar, but unique. In addition, the user can select which processing method for the probe to use and select which data is to be transmitted.

2.1.2 Daisy Chaining Versus Home Run Wiring

If you are contemplating the installation of multiple probes over a large area, consideration should be given to the physical layout of the cables. Digital probes can be connected in a "Daisy Chain" manner, where each probe is spliced onto the cable of the previous probe. This can reduce the amount of cable required along with the corresponding cost. However, this means that splices with have to made, and will likely need to be done in the field. Further if a cable breaks or a splice fails, all probes beyond that point will be out of service until the break is repaired.

"Home Run" wiring means that each probe has a dedicated cable that runs all the way back to the data collection station. The advantages here are just the reverse of "Daisy Chaining". If there is a break in the cable, only that probe is affected. There are no splices to fail. The disadvantage is that the cable requirements and associated costs will be higher.

2.1.3 SDI-12 Hydra Probe II

The SDI-12 version is digital and can be used with Data Loggers that support this communications method. SDI-12 stands for Serial Data Interface at 1200 baud. SDI-12 was developed in cooperation with the USGS (U.S. Geological Survey) and is a standard communication protocol for environmental sensors and data loggers.

2.1.3.1 Transparent Mode

Transparent Mode allows the user to communicate directly with the Hydra Probe. This is necessary in order to assign an address to the probe or modify the probe's configuration.

To program an SDI-12 Version of the Hydra Probe, an SDI-12 compatible device that supports Transparent Mode is required. Most SDI-12 data loggers support Transparent Mode. The SDI-12 protocol is not compatible with common serial data communications, so a device is needed to convert between the two. A typical method is to connect a Personal Computer (PC) to a data logger using a standard nine pin serial data communications cable, and then the probe is connected to the SDI-12 port on the logger, and power is supplied. A terminal program (like Hyper Terminal) is started on the PC. Typically the user must issue a command to the logger to enter Transparent Mode.

See Appendix A for specific information on SDI-12 commands for the Hydra Probe. Please visit www.SDI-12.org for more information about the SDI-12 Protocol. Table 2.2 describes the physical specifications, wire designations, and other information about the digital SDI-12 Hydra Probe II.

Power Requirements	9 to 20 VDC (12VDC Ideal)
Red Wire	+Volts Power Input
Black Wire	Ground
Blue Wire	SDI-12 Data Signal
Baud Rate	1200
Power Consumption	<1 mA Idle, 30 mA Active

Table 2.2 Digital SDI-12 Hydra Probe II Information.

2.1.4 Digital RS-485 Hydra Probe II

Like the SDI-12 Hydra Probe, the RS-485 probe is also digital. The RS-485 communication format has 2 data wires, consumes more power when idle and has a custom communication protocol. Being digital, the RS-485 version shares many of the benefits the SDI-12 version does. The RS-485 sensors can be "daisy chained" or wired to a terminal assembly to simplify installation. The RS-485 Hydra Probe has a maximum cable length of 1000 meters. The user may have specific applications where this capability is advantageous, however, due to the cost of the cable, it may be more cost effective to run short cables and have additional data loggers. See appendix B for more information about commands for the RS-485 Hydra Probe.

Power Requirements	9 to 20 VDC (12VDC Ideal)
Red Wire	+Volts Power Input
Black Wire	Ground
White Wire	Data Signal A non-inverting signal
Green Wire	Data Signal B inverting signal
Baud Rate	9600 8N1
Power Consumption	<10 mA Idle 30 mA Active

Table 2.3 Digital RS-485 Hydra Probe II Information.

2.1.4.1 Addressing and Programming

RS-485 data communications ports are not commonly found on Personal Computers (PC's). To prepare an RS-485 version of the Hydra Probe it will be necessary to program the address. One method to talk to the probe is to connect the probe to a PC via an "RS-485 to RS-232 converter". These devices are available from several vendors specializing in data communications products.

Once the probe is connected and power is applied, a terminal emulation program, such as Hyper Terminal is started on the PC. Certain settings will be need to be set to enable communications with the probe. The following settings are for Hyper Terminal, but most terminal emulation programs should have equivalent settings.

- COM Port should be set to correspond with actual port on the PC where the communications cable is plugged in. For instance COM1, COM2, etc.
- Baud rate should be set to 9600
- Data bits should be set to 8
- Parity should be set to none.
- Stop bits should be set to 1 (one).

- Flow control should be set to none.

In addition, these setting will make the program easier to use. In Hyper Terminal these settings are found under **File / Properties / Settings / ASCII Setup / ACSII Sending**:

- Check "**`Send line ends with line feeds`**". All commands sent to an RS-485 version of the Hydra Probe must end with a "Carriage Return" "Line Feed" pair.
- Check "**`Echo typed characters locally`**". The Hydra Probe does not echo any commands. Checking this enables you to see what you have typed.

2.2 Analog Hydra Probe

The Analog Hydra Probe was the first version made available. The Analog version is useful for a number of applications. Current customers of the Analog probe include users that need to replace or add a sensor to an existing system that was specifically tailored for the analog sensors. One advantage the Analog Hydra Probe has over the digital version is the fast measurement rate. For example, on the beach, ocean researchers can use the analog Hydra Probe to measure the hydrology of sands in the surf zone where they would want to take several measurements between waves. This would entail taking measurements several times per second, something the digital probes cannot do.

2.2.1 Analog Hydra Probe Output

The output of the Analog Hydra Probe is 4 voltages. These four voltages are the raw signal response of the measurement and directly represent the behavior of the reflected electromagnetic standing wave. The four voltages need to be processed by a computer program in order to obtain the parameters of interest such as soil temperature, soil moisture, soil electrical conductivity and the dielectric constants.

Table 2.4 below shows the wiring scheme.

Black Wire	Ground
Red Wire	Power 7 to 30 VDC (12 VDC Ideal)
Blue Wire (Output)	V1 (Raw Voltage 1) Range 0-2.5 volts
Brown Wire (Output)	V2 (Raw Voltage 2) Range 0-2.5 volts
Green Wire (Output)	V3 (Raw Voltage 3) Range 0-2.5 volts
White Wire (Output)	V4 (Raw Voltage 4) Range 0-1 volts
Yellow Wire	Reference Ground
Power Draw Active	35 to 40 mA

Table 2.4 wiring scheme for the Analog Hydra Probe.

An easy way to remember the wiring scheme is the colors of the wires are ordered alphabetically. The black and yellow ground wires may be connected and grounded together or grounded separately. The four voltage data wires need to be wired into four separate voltage sensing connection points on the recording instrument. On the Stevens DOT Logger, the analog ports are labeled A1, A2, A3, and A4. Use the logger data acquisition procedure to obtain the raw voltages values. For more information about the Stevens Dot Logger, see appendix C.

2.3.2 Post possessing raw voltages into the measurements of interest.

The output of the Analog Hydra Probe is 4 voltages, each on a separate color coded wires. V1 V2 and V3 will be between 0 and 2.5 volts DC. V4 will be between 0.1 to 0.8 volts DC. These 4 voltages need to be processed by a series of algorithms to obtain the parameters of interest. Stevens provide two executable programs to perform these calculations:

- HYDRA.EXE
- HYD_FILE.EXE.

HYD_FILE.EXE and HYDRA.EXE as well as the instruction procedure for HYD_FILE.EXE can be downloaded from the Stevens website at: http://www.stevenswater.com

HYD_FILE.EXE is the program used for processing tables of raw voltages collected over time. HYDRA.EXE is the program used for a single measurement of the 4 voltages.

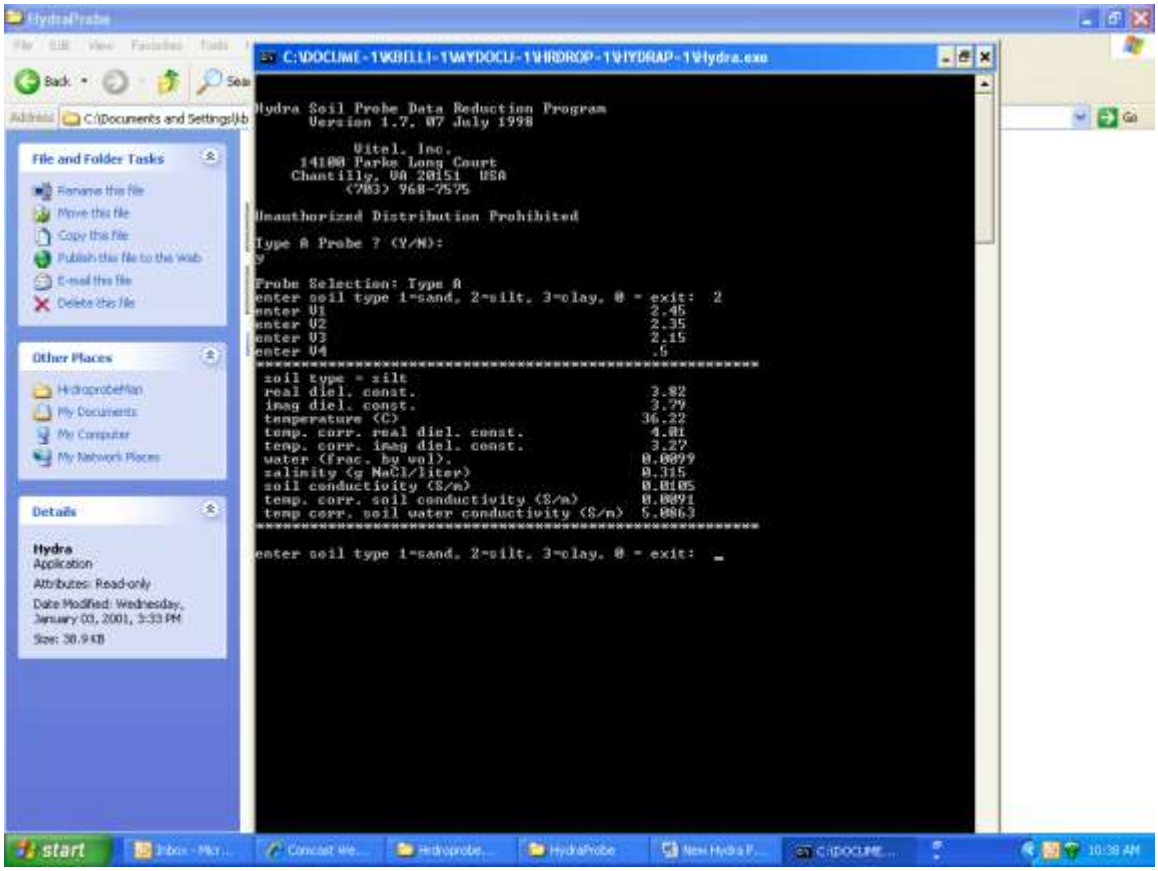
Hydra Soil Probe Data Reduction Program
Version 1.7, 07 July 1998
Vitel, Inc.
14100 Parke Long Court
Chantilly, VA 20151 USA
(703) 968-7575
Unauthorized Distribution Prohibited
Type A Probe ? (Y/N):
Probe Selection: Type A
enter soil type 1=sand, 2=silt, 3=clay, 0 = exit: 2
enter V1 2.45
enter V2 2.35
enter V3 2.15
enter V4 .5
soil type = silt
real diel. const. 3.82
imag diel. const. 3.79
temperature (C) 36.22
temp. corr. real diel. const. 4.01
temp. corr. imag diel. const. 3.27
water (frac. by vol). 0.0899
salinity (g NaCl/liter) 0.315
soil conductivity (S/m) 0.0105
temp. corr. soil conductivity (S/m) 0.0091
temp corr. soil water conductivity (S/m) 5.0863
enter soil type 1=sand, 2=silt, 3=clay, 0 = exit:

FIG. 2.1 HYDRA.EXE Input V1, V2, V3, V4 and Output Parameters.

To use HYDRA.EXE simply open the file and follow the prompts. The first prompt will ask "**`Type A Probe ? (Y/N):`**". Type Y. Almost all of the Analog Hydra Probes are type A. Type A probes use a 2.5 volt reference for the temperature sensing element. A non-type A probe uses a 5 volt reference. Next, enter the soil type and then the four voltage values. After the user

responds to all of the prompts, the output is displayed. The displayed output consists of the dielectric constants, the temperature, the soil moisture, and the soil electrical conductivity.

2.2.2 Trouble Shooting the Analog Hydra Probe

If the Hydra Probe appears to be malfunctioning, there are three likely causes:

- communication with the logger
- soil hydrology
- a malfunctioning probe.

See the section about soil hydrology.

Programming a data logger is not a trivial task. The data logger needs to extract 4 raw voltages from four analog ports on the logger with the desired timing interval. If the user is unable to get a response from the Hydra Probe, it is recommended to first physically check wire connections from the probe to the logger. The user may also want to cycle the power to the probe by disconnecting and reconnecting both ground wires. If the connections are sound, the user will next need to check the logger's setup. *Are the data ports enabled? Are the data ports scaled properly in the appropriate units? Are the probes and logger adequately powered? Is the data properly recorded on the logger?* If the logger has GUI based operation software, there may be a help function. If the logger only accepts terminal command scripts in a terminal window, refer to the logger's manual or manufacturer. Also, make sure the computer is properly connected to the logger. *Is the computer on the proper COM port? What about the Baud rate? Does the logger need a NUL modem or optical isolator in order to be connected to a computer?* Most of the technical support questions Stevens receives are not due to malfunctioning probes but rather an incorrect data logger setup.

A good way to verify if the probe is working properly is to submerge the probe in distilled water* in a plastic container and check the dielectric constants. Once the probe is submerged, connect the black and yellow wires to a ground and connect the red wire to a +12 volt DC power source. Use a voltmeter to measure the raw voltage on the 4 data wires. A common hand held unit is adequate. Use HYDRA.EXE to process the voltages. The temperature corrected real dielectric constant should be 75 to 85 and the imaginary dielectric constant should be less than 5. The user may use this method to verify if the probe is functioning properly, and to verify the logger output. If the probe is buried in the soil, the user can obtain the 4 raw voltage outputs with a multimeter and compare them to the logger's output.

*The user may also use tap water for this procedure, however, it is important to note that tap water contains dissolved material and trace contaminants that might affect the dielectric constants.

2.3 Other Applications and Alternative Calibrations

It may be possible to use the Hydra Probe for applications in media other than mineral soil. Some examples include peat, decomposed plant material, grain, compost, ice cream/ food products or any material that has a small dielectric constant compared to that of water. The calibration curves used to calculate soil moisture may not be valid for material different from mineral soil; however, the dielectric constants are provided allowing the user to calibrate the probe

accordingly. The calibration curves will mathematically have the appearance of equation [2.1] or [2.2]

$$\theta = A + BE_r + CE_r^2 + DE_r^3 \quad [2.1]$$
$$\theta = AE_r^{1/2} + B \quad [2.2]$$

Where θ is moisture E_r is the real dielectric constant and A,B,C, and D are coefficients. If the user wishes to use the Hydra Probe to measure moisture in a matrix that is not mineral soil, the user must empirically and experimentally solve equation [2.1] or equation [2.2]. Also, The user should review the matrix compatibility requirements of the probe in section 3.1.

2.3.1 Frozen Soil

The Hydra Probe can also be used to determine if soil is frozen. Once ice reaches 0^o Celsius, it will begin to thaw and the real dielectric constant will increase from 5. The temperature alone may not indicate whether or not the soil is frozen. As the soil begins to thaw, the soil moisture and the real dielectric constant should return to values similar to what they were before the soil froze.

3 Installation

The Hydra Probe is easy to install and the use of installation tools are seldom required.

3.1 Avoid Damage to the Hydra Probe:

- Do not subject the probe to extreme heat over 70 degrees Celsius (160 degrees Farenheit).
- Do not subject the probe to fluids with a pH less than 4.
- Do not subject the probe to strong oxidizers like bleach, or strong reducing agents.
- Do not subject the probe to polar solvents such as acetone.
- Do not subject the probe to chlorinated solvents such as dichloromethane.
- Do not subject the probe to strong magnetic fields.
- Do not use excessive force to drive the probe into the soil because the tines could bend. If the probe has difficulty going into the soil due to rocks, simply relocate the probe to an area slightly adjacent.
- Do not remove the Hydra Probe from the soil by pulling on the cable.

While the direct burial cable is very durable, it is susceptible to abrasion and cuts by shovels. The user should use extra caution not to damage the cable or probe if the probe needs to be excavated for relocation.

Do not place the probes in a places where they could get run over by tractors or other farm equipment. The Hydra Probe may be sturdy enough to survive getting run over by a tractor if it is buried; however, the compaction of the soil column from the weight of the vehicle will affect the hydrology and thus the soil moisture data.

3.1.1 Lightning

Lightning strikes will cause damage or failure to the Hydra Probe or any other electrical device, even though it is buried. In areas prone to lightning, serge protection and /or base station grounding is recommended.

3.2 Wire Connections

3.2.1 Analog Probe Wire Connection

Table 2.4 in section 2.4.3 shows the wiring scheme for the Analog Hydra Probe. The four voltage data wires need to be wired into four separate data ports on the logger. On the Stevens DOT Logger, the analog ports are labeled A1, A2, A3, and A4. The red power wire should be connected to a +12 volt power supply and the black and yellow wires should be connected to a ground. For more information, refer to the data loggers operation manual. For DOTSET and the Stevens DOT Logger refer to Appendix C.

3.2.2 SDI-12 Hydra Probe Wiring Connections

Table 2.2 and section 2.1 provide important information about the SDI-12 Hydra Probe. Connect the red wire to a +12 volt DC power supply, connect the black wire to a ground, and connect the blue wire to the SDI-12 port or the Data Logger. The SDI-12 data port on the Stevens DOT logger is conveniently located on the right side of front face plate. The advantage of SDI-12

communications is that multiple probes can be connected to a single port on data logger. The probes may be "daisy chained" together, or they may all be connected to a central terminal assembly. The single SDI-12 data port on the DOT Logger can accommodate 150 SDI-12 Channels. To have 150 SDI-12 channels means that 50 probes set to measure soil moisture, conductivity and temperature can all be wired together on a multiplexer with a single data wire going into the single SDI-12 data port. For more information, refer to the data loggers operation manual. For more information about the Stevens DOT Logger refer to Appendix C.

For more than 6 Hydra Probes, the user may find it easier to have the terminal assembly in a separate enclosure from the logger, telemetry and power supply.

3.2.3 RS-485 Hydra Probe wiring Connections

Table 3.1 and section 2.1.4 provide important information about the RS-484 Hydra Probe. Connect the red wire to a +12 volt DC power supply, and connect the black wire to a ground. The green and white wires are the data wires.

Power Requirements	9 to 20 VDC (12VDC Ideal)
Red Wire	+Volts Power Input
Black Wire	Ground
White Wire	Data Signal A non-inverting signal
Green Wire	Data Signal B inverting signal
Baud Rate	9600
Power Consumption	<10 mA Idle 30 mA Active
Control system settings	8 DATA BITS
Control system settings	One Stop Bit
Control system settings	NO Parity

Table 3.1 Digital RS-485 Hydra Probe II Information.

Like SDI-12, the RS-485 communication format is also digital, therefore the probes' data wires can be "daisy chained" or connected together at a terminal assembly. See Appendix B for RS-485 command structure.

3.3 Soil and Topographical Considerations

3.3.1 Soil Moisture Calibration

There are four calibration curves depending on the texture of the soil. The calibrations curves are polynomials that include the real dielectric constant and several coefficients (Topp 1980, Seyfried and Murdock 2004). The four user selectable soil texture settings are Sand, Silt, Clay, and Loam. The texture is determined by the percentage of sand silt and clay there is in the soil. Figure 3.1 shows the corresponding percentages to the different textures. If you are unsure of your soil texture, determining which soil setting that is best for your soil is easy and there are a number of different ways to make the determination (Birkeland 1999).

a) A detailed soil survey for your area can be downloaded for free from the US Department of Agriculture at http://soildatamart.nrcs.usda.gov/
b) Many times, it will be obvious. Sand looks different from clay.
c) Grab a baseball size portion of the soil in your hands. Wet the soil with water and work the moist soil with your hands. The stickier it is, the more clay there is. The "soapier" the soil feels the higher the silt content. Grittiness is indicative of sand.

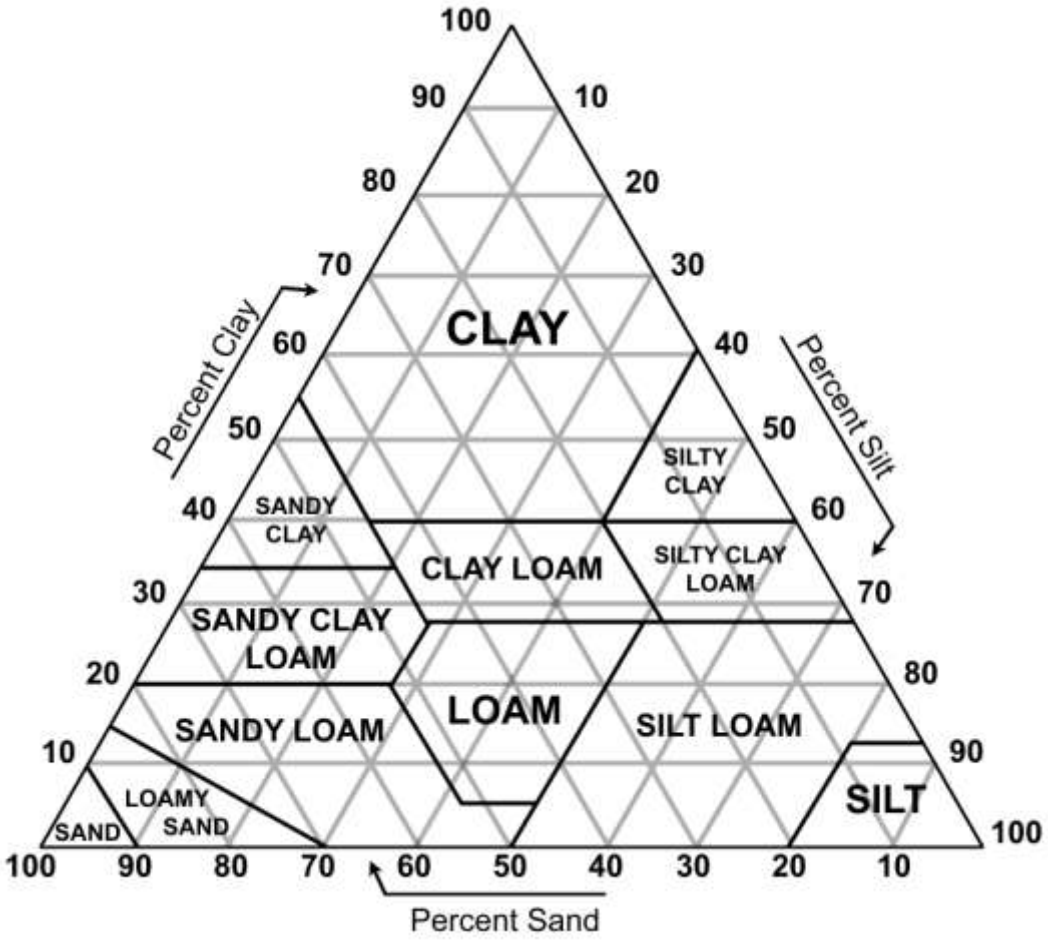

Figure 3.1 Soil Texture Triangle

If you have a mixture of sand, silt and clay or if you are unsure what the texture of your soil is, then use the Loam setting. The Sand, Silt and Clay settings are only suitable for soils that are comprised almost entirely of that one material. For most mixtures the Loam setting will give better results. The Loam setting is applicable for Loam, Clay Loam, Silty Clay Loam, Silt Loam, Sandy Loam, Sandy Clay Loam, Sandy Clay and Silty Clay textures.

If unsure as which calibration to use, the loam calibration will accommodate most soils. The Loam calibration is the default calibration, which means, the Hydra Probe is preset to the loam soil type setting when it leaves the factory. Figure 3.2 shows the textures where the loam setting works best.

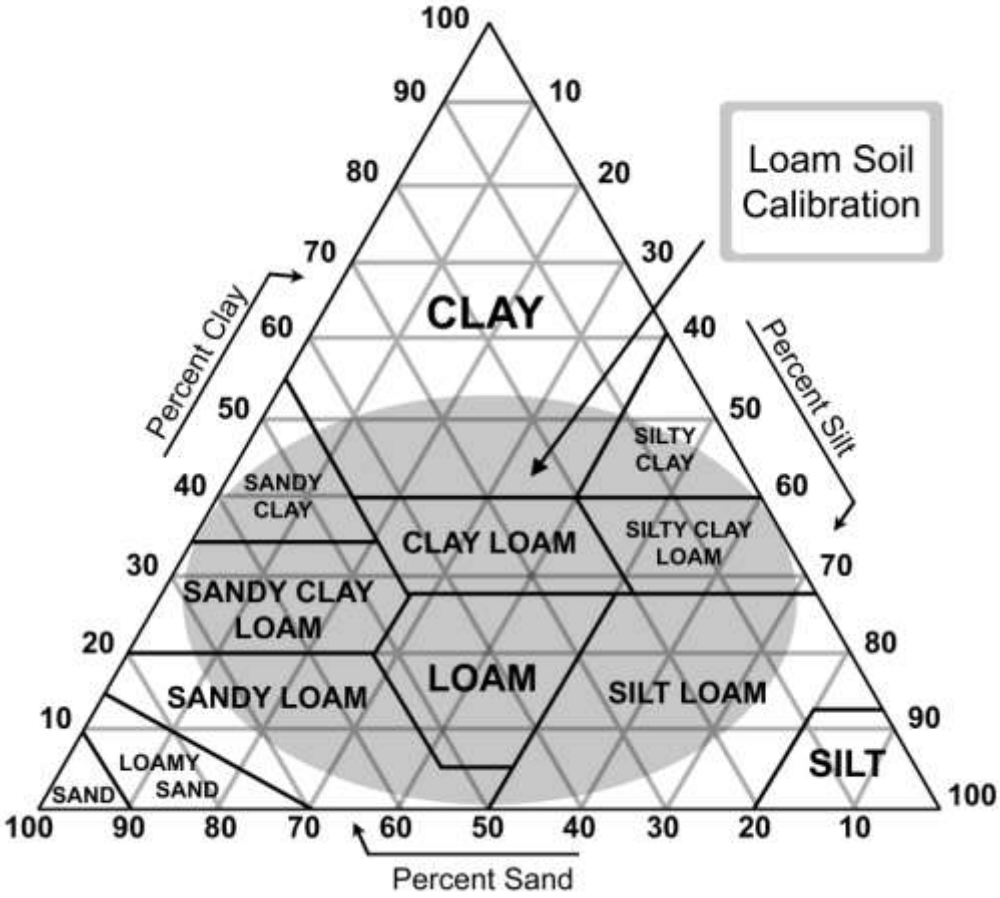

Figure 3.2 The shaded circle in the soil texture triangle is the region where the Loam soil calibration works best. Most users should use the loam calibration. The Hydra Probe is preset to use the loam soil calibration when shipped.

3.3.2 Soil Classifications

Between the four preset calibrations and the custom calibration option, the Hydra Probe can measure soil moisture in almost any kind of soil. There are thousands of different kinds of soil through out the world, and almost every nation has some kind of classification system. The most wide spread and most current soil classification system is the Orders of American Soil

Taxonomy. In this system, all of the worlds' soils are broken into 12 orders based on climate, topography, biology and soil chemistry. Table 3.2 lists the orders.

The Hydra Probe can accommodate all of the soil orders. Andisols, gelisols and histosols are soil that may have soil moistures and properties that depart from the Hydra Probe's built in calibration curves. If the bulk density is extremely low giving the soil an effective porosity greater than 0.5, the user will need a custom calibration If a custom calibration is required see Section 2.3. If the Hydra Probe needs to be switched from the default Loam calibration setting, see the RS-485 or SDI-12 command sections in the appendix.

Soil Order	Climate or Regime	Soil Characteristics	Hydra Probe Calibration
Entisol	Sandy Young Soil	Stream Flood Plain	Sand
Inceptisol	Silty Young Soil	Evidence of red color	Sand or Silt
Vertisol	Shrink/Swell Clay	Homogenized Soil	Loam or Clay
Histosol	Wetland Soil	Anoxic Reduced State	Loam or Custom
Aridisol	Desert Soil	Higher pH	Sand
Mollisol	Grass land Soil	Higher pH	Loam or Silt
Spodosol	Needle Leaf Forest Soil	Low pH	Loam or Silt
Alfisol	Forest Soil	Low pH	Loam or Silt
Ultisol	Old Forest Soil	Low pH	Loam
Oxisol	Ancient Forest Soil	Red, Oxidized	Loam
Gelisol	Soil With Permafrost	Organic Rich	Loam or Custom
Andisol	Volcanic Ash Soil	Low Density	Loam or Custom

Table 3.2 The 12 Orders of Soil Taxonomy, Characteristics and Hydra Probe Calibration setting.

3.4 Installation of the Hydra Probe in Soil

3.4.1 Topography and Groundwater Hydrology

The land topography often dictates the soil hydrology. Depending on the users' interest, the placement of the Hydra Probe should represent what would be most useful. For example, a watershed researcher may want to use the Hydra Probe to study a micro climate or small hydrological anomaly. On the other hand, a farmer will want to take measurements in an area the best represents the condition of the crops as a whole.

Other factors to consider would be tree canopy, slope, surface water bodies, and geology. Tree canopy may affect the influx of precipitation/irrigation. Upper slopes may be better drained than depressions. There may be a shallow water table near a creek or lake. Hill sides may have seeps or springs.

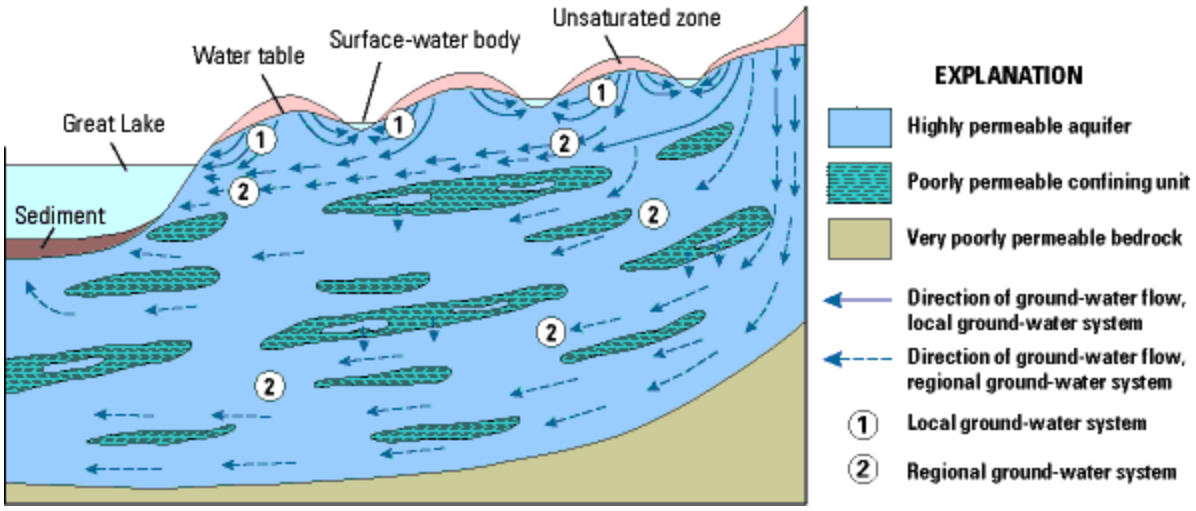

Figure 3.3 Groundwater pathways and Surface water. Taken from USGS Report 00-4008

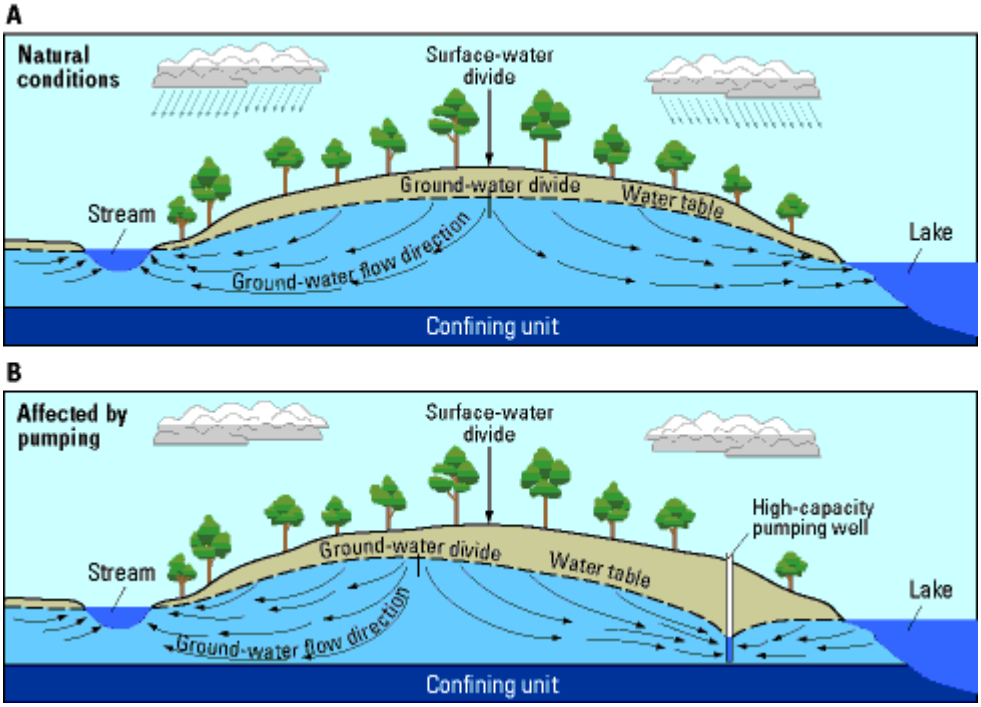

Figure 3.4 Groundwater flow direction and surface water body. Taken from USGS report 00-4008.

Figures 3.3 and 3.4 illustrate subsurface water movement in the water table. The Hydra Probe data is most meaningful in the unsaturated zone where soil moisture values will fluctuate. If the water table rises to the depth of the Hydra Probe, the Hydra Probe soil moisture measurements will be at saturation and will be indicative of the effective porosity. If the user is interested in groundwater level measurements in wells, a water depth sensor might provide the necessary information.

3.4.2 Installation of the Hydra Probe into Soil.

The most critical thing about the installation of the Hydra Probe is the soil needs to be undisturbed and the base plate of the probe needs to be flush with the soil. To install the probe into the soil, first select the depth (see section 3.4.3 for depth selection). A post hole digger or spade works well to dig the hole. If a pit has been prepared for a soil survey, the Hydra Probes can be conveniently installed into the wall of the survey pit before it is filled in. Use a paint scraper to smooth the surface of the soil where it is to be installed. It is important to have the soil flush with the base plate because if there is a gap, the Hydra Probe signal will average the gap into the soil measurement and create errors.

Figure 3.5 Hydra Probe Installed in undisturbed soil.

Push the tines of the Hydra Probe into the soil until the base of the tines is flush with the soil. The tines should be parallel with the surface of the ground, i.e. horizontal. Avoid rocking the probe back and fourth because this will disturb the soil and create a void space around the tines. Again, it is imperative that the bulk density of the soil in the probe's measurement volume remain unchanged from the surrounding soil. If the bulk density changes, the volumetric soil moisture measurement and the soil electrical conductivity will change.

The user may also want to run the Hydra Probe cable through a metal conduit like the one shown in figure 3.6 to add extra protection to the cable.

3.4.3 Hydra Probe Depth Selection

Like selecting a topographical location, selecting the sensor depth depends on the interest of the user. Farmers will be interested in the root zone depth while soil scientists may be interested in the soil horizons.

Depending on the crop and the root zone depth, in agriculture two or three Hydra Probes may be installed in the root zone and one Hydra Probe may be installed beneath the root zone. The amount of water that should be maintained in the root zone can be calculated by the method described in section 4.3. The probe beneath the root zone is important for measuring excessive irrigation.

Figure 3.6 Six Hydra Probes installed into 6 distinct soil horizons.

The soil horizons often dictate the depths of the Hydra Probes' placement. Soil scientist and groundwater hydrologist are often interested in studying soil horizons. The Steven Hydra Probe is an excellent instrument for this application because of the accuracy and precision of the volumetric water fraction calibrations. Soil horizons are distinct layers of soil that form naturally in undisturbed soil over time. The formation of soil horizons is called soil geomorphology and the types of horizons are indicative of the soil order (see table 3.2). Like other natural processes, the age of the horizon increases with depth. The reason why it is so useful to have a Hydra Probe in each horizon is because different horizons have different hydrological properties. Some horizons will have high hydraulic conductivities and thus have greater and more rapid fluctuations in soil moisture. Some horizons will have greater bulk densities with lower effective porosities and thus have lower saturation values. Some horizons will have clay films that will

retain water at field capacity longer than other soil horizons. Knowledge of the soil horizons in combination with the Hydra Probes accuracy will allow the user to construct a more complete picture of the movement of water in the soil. The horizons that exist near the surface can be 6 to 40 cm in thickness. In general, with increasing depth, the clay content increases, the organic mater decreases and the base saturation increases. Soil horizons can be identified by color, texture, structure, pH and the visible appearance of clay films.

More information about soil horizons is provided by the USDA National Resource Conservation Service at http://soils.usda.gov/education/resources/k_12/lessons/profile/

More information about the soil horizons in your area can be found by in a soil survey. A soil survey for your area can be found at http://soildatamart.nrcs.usda.gov/

Soil Horizon	**Property**
O	Decaying plants on or near surface
A	Top Soil, Organic Rich
B	Subsoil, Most Diverse Horizon and the Horizon with the most sub classifications
E	Leached Horizon (light in color)
C	Weathered/aged parent material

Table 3.3 Basic description of soil horizons.

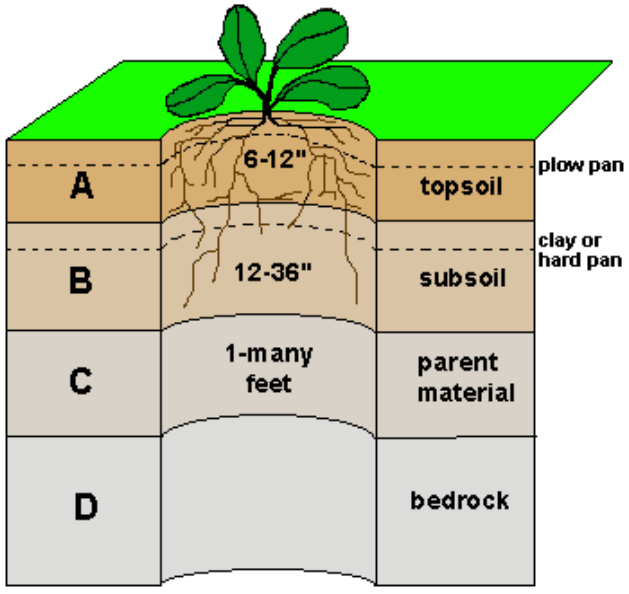

Figure 3.7 Soil Horizons.

Figure 3.8 Illustration of soil horizons. In this frame, the soil horizons are very distinct and show the geological history of the soil.

3.4.4 Back Filling the Hole after the Probes are Installed.

After soil is removed from the ground and piled up next to the hole, the horizons and soil become physically homogenized. The bulk density decreases considerably because the soil structure has been disturbed. After the probes are securely installed into the wall of the pit, the pit needs to be backfilled with the soil that came out it. It is impossible to put the horizons back the way they have formed naturally, but the original bulk density can be approximated by compacting the soil. For every 24 cm (1 foot) of soil put back into the pit, the soil should be compacted. Compaction can be done by trampling the soil with feet and body weight. Mechanical compactors can also be used, though typically they are not required. Extra care must be taken not to disturb the probes that have exposed heads, cables and conduits when compacting the soil. If the probes were installed in a post hole, a piece of wood, such as a post, can be used to pack the soil.

If the soil is not trampled down while it is being back filled, the compaction and bulk density of the backfill will be considerably less than the native undisturbed soil around it. After a few months, the backfilled soil will begin to compact on its own and return to a steady state bulk density. The Hydra Probe will effectively be residing in two soil columns. The tines will be in the undisturbed soil column, and the head, cable and conduit will be in the backfill column that is undergoing movement. The compaction of the backfilled soil may dislodge the probe and thus affect the measurement volume of the probe. After the probes are installed, avoid foot traffic and vehicular traffic in the vicinity of the probes.

4 Measurements, Parameters, and Data Interpretation

4.1 Analog Hydra Probe Output

Parameters V1, V2, V3 and V4 returned by the digital probes correspond to the voltages read from the analog probe. In almost all applications, V1, V2, V3, V4 and V5 by themselves are of no interest to most users of the digital Hydra Probe. See section 2.2.3 for analog processing information.

4.1.1 Raw Voltages V1, V2, and V3.

The first three voltages are the raw signal responses. The Hydra Probe is a Frequency Domain Reflectometer in that it is measuring the behavior of a standing wave generated from the reflection of an electromagnetic wave at a radio frequency of 50 MHz. The 50 MHz electromagnetic wave propagates along the wave guide. The soil absorbs most of the wave. The portion of the wave that reflects back down the wave guide encounters the emission propagation creating a standing wave. The first three voltages represent the behavior of the standing wave and thus the complex dielectric permittivity. The direct measurement of the complex dielectric permittivity from the raw signal responses is the basis behind the other parameters and makes the Hydra Probe unique among other FDR type methods (Campbell, 1990, Seyfried and Murdock, 2004).

4.1.2 V4

V4 is the raw signal response of the diode thermistor. The diode thermistor is located within the probe housing. V4 is used to make temperature corrections to the electronics. See Diode temperature below for more information.

4.1.3 V5

V5 is the raw signal response of the soil thermistor. The soil thermistor is located in the stainless steel base plate between the tines. It is in close proximity to the soil providing accurate soil temperature readings. Complex dielectric permittivity is influenced by temperature. Not only can the Hydra Probe measure soil temperature, it can make temperature corrections to the calibration curves based on the temperature corrections of the complex dielectric permittivity. See temperature corrected real and imaginary dielectric constant for more information. See section 2.2.3 for analog processing information.

4.1.4 ADC Reading 1 through 5

The ADC Reading 1 through 5 are the analog to digital values at 10 bits. They are the binary numbers that correspond to V1 through V5. They are used by Stevens for development or trouble shooting purposes.

4.1.5 Diode Temperature

The Diode Temperature is the temperature of the electronics within the Hydra Probe housing. It corresponds to V4. Because the electronics produces a negligible amount of heat while taking a reading, the diode temperature is usually very close, if not the same value as soil temperature.

The diode temperature is used by the Hydra Probe to make algorithmic temperature correction to the electronics.

4.2 Soil Temperature

The user can select Fahrenheit or Celsius. Diurnal (daily) temperature fluctuations between daytime highs and nighttime lows may be observed with the Hydra Probe's temperature data. These fluctuations will become less pronounced with depth. Vegetation, tree canopy, and soil moisture are factors that will effect the diurnal soil temperature fluctuations. For example, in the American Southwest, A Hydra Probe buried at a five inch depth will have very pronounced temperature fluctuations between the nighttime lows and the daytime highs if there is no vegetation insulating the soil. Seasonal trends can also be observed in soil temperature data.

4.3 Soil Moisture

4.3.1 Soil Moisture Units

The Hydra Probe provides accurate soil moisture measurements in units of water fraction by volume (wfv or m^3m^{-3}). That is, a percentage of water in the soil displayed in decimal form. For example, a water content of 0.20 wfv means that a one liter soil sample contains 200 ml of water. Full saturation (all the soil pore spaces filled with water) occurs typically between 0.3-0.45 wfv and is quite soil dependent.

There are a number of other units used to measure soil moisture. They include % water by weight, % field capacity, % available (to a crop), inches of water to inches of soil, and tension (or pressure). They are all interrelated in the sense that for a particular soil, knowledge of the soil moisture in any one of these units allows the soil moisture level in any of the other unit systems to be determined. It is important to remember that the conversion between units can be highly soil dependent.

The unit of water fraction by volume (wfv) was chosen for the Hydra Probe for a number of important reasons. First, the physics behind the soil moisture measurement dictates a response that is most closely tied with the wfv content of the soil. Second, without specific knowledge of the soil, one can not convert from wfv to the other unit systems. Third, the unit wfv allows for direct comparison between readings in different soils. A 0.20 wfv clay contains the same amount of water as a 0.20 wfv sand.

However, the same thing can not be said about the other measurement units. For example, to use the unit common in tensiometer measurements, a one Bar sand and a one Bar clay will have vastly different water contents. The wfv unit can also be readily used to estimate the effects of precipitation or irrigation. For example, consider a soil that is initially 0.20 wfv, and assume a 5 cm rainfall that is distributed uniformly through the top one meter of soil. What will the resultant soil moisture in the top one meter of soil be? 5 cm is 0.05 of one meter, so the rainfall will increase the soil moisture by 0.05 wfv to result in a 0.25 wfv soil. For other units, this calculation can be much less straightforward, particularly when soil moisture is measured as a tension.

4.3.2 Soil Moisture Measurement Considerations

Soil moisture measurements are important for a number of applications and for a number of different reasons. Some applications include; land slide studies, erosion, water shed studies, climate studies, predicting weather, flood warning, crop quality and yield optimization, irrigation, and soil remediation to name a few.

Soil moisture values are particularly important for irrigation and the health of the crop. Equations [4.1], [4.2] and [4.3] can help determine when to irrigate. The following are terms commonly used in soil hydrology:

- Soil Saturation, refers to the situation where all the soil pores are filled with water. This occurs below the water table and in the unsaturated zone above the water table after a heavy rain or irrigation event. After the rain event, the soil moisture (above the water table) will decrease from saturation to field capacity.
- Field Capacity (FC in equations below) refers to the amount of water left behind in soil after gravity drains saturated soil.
- Permanent Wilting Point (PWP in equations below) refers to the amount of water in soil that is unavailable to the plant.
- The Allowable Depletion (AD in the equations below) is calculated by equation [4.1]. The allowable depletion represents the amount of soil moisture that can be removed by the crop from the soil before the crop begins to stress.
- Lower soil moisture Limit (LL from [4.3]) is the soil moisture value below which the crop will become stressed because it will have insufficient water. When the lower limit is reached, it is time to irrigate.
- The Maximum Allowable Depletion (MAD) is the fraction of the available water that is 100% available to the crop.
- Available Water Capacity (AWC) is the amount of water in the soil that is available to the plant.

The lower soil moisture limit is a very important value because dropping below this value will affect the health of the crops. Equations 4.1, 4.2, and 4.3 and the example show how to calculate the lower soil moisture limit.

Texture	Clay	Silty Clay	Clay Loam	Loam	Sandy Loam	Loamy Sand	Sand
MAD	0.3	0.4	0.4	0.5	0.5	0.5	0.6

A
D

$$= (FC - PWP) \times MAD \qquad [4.1]$$

$$AWC = FC - PWP \qquad [4.2]$$

$$LL = FC - AD \qquad [4.3]$$

Table 4.1 Maximum allowable depletions for different soil textures

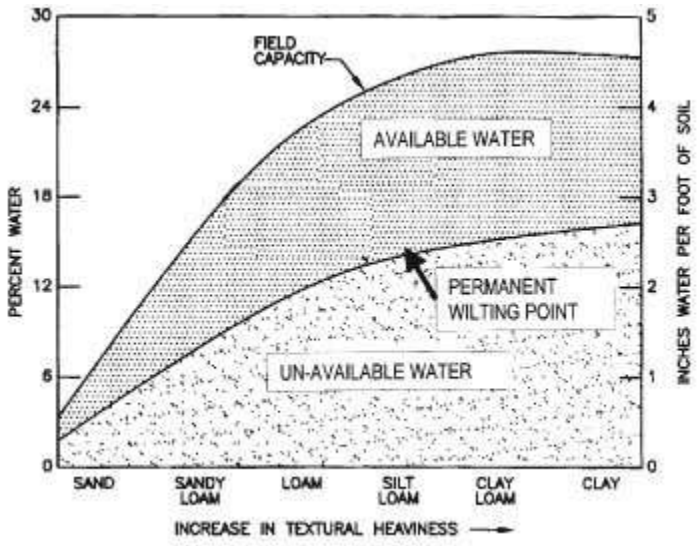

Figure 4.1 soil textures and the available water.

For example, let us suppose your soil is a sandy loam. From table 4.1, MAD = 0.5, From Figure 4.1 (or a soil surrey) PWP = 13% and the field capacity is 25%. Using equation [4.1] yields; AD = (25-13) x 0.5 = 6% . The lower limit would then be calculated by equation [4.3].
LL = 25 - 6 = 19%. This means for a sandy loam, if the soil moisture drops below 19% (or Hydra Probe reading of 0.19), the crop may become stressed and it is time to irrigate. Never let the soil moisture drop below the permanent wilting point.

4.4 Soil Salinity (g/L NaCl)

The Soil Salinity (g/L NaCl) parameter is the salinity of a 1:1 soil/water slurry. It is the "total dissolved solids" (TDS) in the form of dissolved salts. The soil salinity parameter is primarily used with the portable versions of Hydra Probe. The soil salinity parameter is not applicable for in situ measurements in a permanent/semi permanent installation in soil. The soil salinity is approximated:

$$\text{Soil Salinity (g/L)} \approx \text{EC (S/m)} \times 6.4 \qquad [4.4]$$

Equation [4.4] is found in the literature (McBride 1994) and works well if the soil is not extremely acidic or extremely alkaline.

To use the Soil Salinity Parameter, mix one part soil with one part water and take a reading with the Hydra Probe's tines completely submerged in the water extract. Avoid using metal containers to take the reading and/or make the slurries because the metal may interfere with the measurements.

In situ soil salinity is usually inferred by the in situ soil electrical conductivity in S/m (see soil electrical conductivity section below).

4.5 Soil Electrical Conductivity (Temperature corrected)

The Hydra Probe measures the in situ electrical conductivity in units of Siemens per meter. Soil electrical conductivity is indicative of dissolved salts, dissolved solids, and fertilizers (McBride 1994). It may also be indicative of very high pH conditions. The soil electrical conductivity is calculated from the temperature corrected imaginary dielectric constant [$E_{i(tc)}$] by the theoretical expression:

$$EC = 2\pi f \varepsilon_0 E_{i(TC)} \quad [4.5]$$

Where EC is the electrical conductivity, f is the frequency (50 MHz for the Hydra Probe) and ε_0 is the dielectric constant of a vacuum. For more information on soil electrical conductivity considerations, see soil electrical conductivity section below.

As the temperature increases, the molecular vibration increases (Levine, 1993). The molecular vibration has a complex affect on both the orientation polarization and on the imaginary dielectric constant. The temperature corrections are based on the small incremental changes of *Ei* and *Er* with temperature.

5 Theory of Operation

5.1 Real and Imaginary Dielectric Constants

The Hydra Probe is a dielectric constant sensor (Seyfriend, Grant, and Humes 2005) measuring the complex dielectric permittivity. The complex dielectric permittivity is the raw electrical parameter that has real and imaginary components (the real dielectric constant and the imaginary dielectric constant). These two parameters serve to fully characterize the electrical response of soil and are measured from the response of a reflected standing electromagnetic wave at a radio frequency of 50 MHz. Both the real and imaginary dielectric constants are dimensionless quantities.

The Hydra Probe is different from all other soil sensors because it measures both components of the complex dielectric permittivity of the soil. In other words, The Stevens Hydra Probe uses the reflected properties of a radio waves to measure soil moisture and soil electrical conductivity simultaneously.

The complex dielectric permittivity contains both real and imaginary components where the real component is related to the capacitance (soil moisture) and the imagery component is related to the electrical conductivity

Capacitance is the measure of electric charge that can be stored in a media. The dielectric constant is related to capacitance by the following equation:

$$\varepsilon_o E = C_x \qquad [5.1]$$

ε_o is the capacitance in a vacuum, E is the dielectric constant, and C_x is the measured capacitance of the media in Farads. Every material has a dielectric constant. As the dielectric constant increases, the capacitance of the media increases. In other words, the capacitance increases as a factor of the dielectric constant.

In the presence of an electromagnetic wave, the dielectric constant becomes frequency dependent. The frequency dependence of the dielectric constant is generally termed complex dielectric permittivity because the relationship between frequency and the dielectric constant becomes a complex modulus containing both real and imaginary components.

The real dielectric constant represents the molecular orientation polarizability. The orientation polarization of a water molecule in the presence of an electromagnetic wave is much greater than the polarization of dry soil, which is mostly due to electronic and atomic polarization. The real dielectric constant of dry soil can be from 1 to 5 where the real dielectric constant for pure water is about 80. The real dielectric constant of soil is mostly attributed to the presence of water. Figure [5.1] illustrates the different kinds of polarization molecules can under go upon receiving electromagnetic energy. The general equation that describes complex dielectric permittivity is:

$$K^* \varepsilon_0 = E^*, \quad K^* = E_r - jE_i \qquad [5.2]$$

Where (E_i) is imaginary dielectric constant, $j = -1^{1/2}$ and is the imaginary number, and (E_r) is the real dielectric constant.

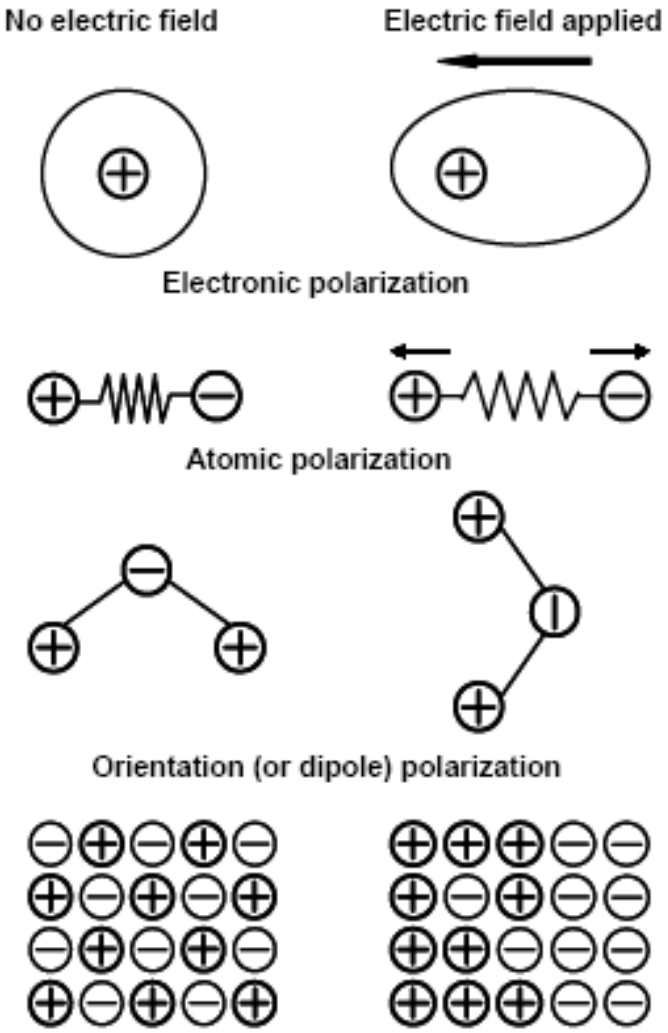

Figure [5.1]. Illustration of polarization. The real dielectric constant of soil is mostly due to orientation polarization of water (Taken from Lee et al. 2003)

The imaginary dielectric constant is directly related to the conductivity of the medium, the higher the imaginary dielectric constant, the higher the conductivity. Assuming the molecular relaxation is negligible, the imaginary dielectric constant is a function of frequency and electrical conductivity by the following relationship:

$$E_i = \mathrm{EC}/\ 2\pi f\, \varepsilon_0 \quad [5.3]$$

Where EC is the electrical conductivity, f is the frequency (50 MHz for the Hydra Probe) and ε_0 is the dielectric constant in a vacuum. As can be shown by equation [5.3], as the frequency increases, the E_i rapidly decreases. Conversely, if the frequency decreases or if cations are introduced, the E_i will increase thus affecting the real dielectric constant of the matrix.

The Hydra Probes' design features such as the geometry of the wave guide and the frequency at 50 MHz allows the Hydra Probe to simultaneously measure both real and imaginary dielectric constants (Campbell, 1990).

5.2 Real Dielectric and Imaginary Constants (Temperature corrected)

Since both the real and imaginary dielectric constants will vary somewhat with temperature, the user of the Hydra Probe has the option of selecting the temperature corrected values for the real and imaginary dielectric constants. The uncorrected and the corrected dielectric values may be of interest for some researchers. The soil moisture calibrations are based on the temperature corrected values because the calibration curves were established at a constant temperature. Similarly, the temperature corrected imaginary dielectric constant was used for the electric conductivity measurement.

As the temperature increases, the molecular vibration increases (Levine, 1993). The molecular vibration has a complex effect on both the orientation polarization and on the imaginary dielectric constant. The temperature corrections are based on the small incremental changes of *Ei* and *Er* with temperature.

5.3 Soil Electrical Conductivity.

The Hydra Probe measures the in situ electrical conductivity in units of Siemens per meter (S/m). Soil electrical conductivity is indicative of dissolved salts, dissolved solids, and fertilizers (McBride 1994). It may also be indicative of very high pH conditions. The soil electrical conductivity is calculated from the imaginary dielectric constant [E_i]. by the theoretical expression:

$$EC = 2\pi f \varepsilon_0 E_i \quad [5.4]$$

Where EC is the electrical conductivity, f is the frequency (50 MHz for the Hydra Probe) and ε_0 is the dielectric constant of a vacuum.

5.3.1 Electrical Conductivity Pathways in Soil

The electric conductivity of soil is complex. Figure [5.2] shows the three pathways the electrical conductivity can propagate in soil. The bulk density, the porosity, the tortuosity, the water content, and the dissolved ion concentration working in concert with the different pathways, dramatically influences the electrical conductivity of a soil.

Pathway 1 is the electrical pathway that goes from water to the soil and back through the water again. The electrical conductivity contribution of pathway 1 is a function of the conductivity of the water and soil. As water increases, pathway 1 increases which may increase the electrical conductivity of the soil as a whole.

Pathway 2 is the pathway that is attributed to the electrical conductivity of the soil water. Increasing the dissolved salts will increase the conductivity of pathway 2; however, like pathway

1, increases in the soil water content will increase the size of the pathway thus increasing the electrical conductivity. That is to say, that there are two factors influencing the electrical conductivity of pathway 2, namely the dissolved salt concentration and the size of the pathway attributed to the amount of water in the soil.

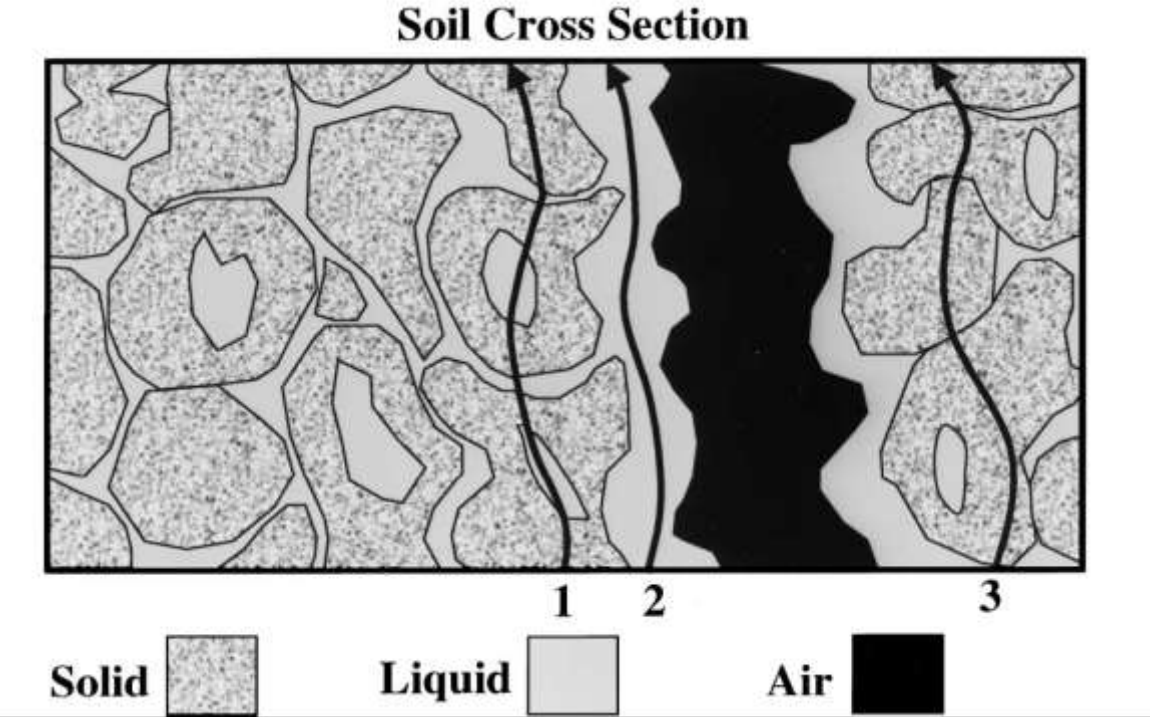

Figure 5.2 Pathway3 of electric conductivity in soil matrix. 1 water to solid, 2 soil moisture, 3 solid. Taken from Corwin et al. (2003).

Pathway 3 is the electrical conductivity of the soil particles. Like the other pathways, the contribution of pathway 3 in influenced by a number of factors that include bulk density, soil type, oxidation/reduction reactions and translocation of ions.

The electric conductivity measurements provided by the Hydra Probe is the electrical conductivity of the dynamic soil matrix as a whole. No in situ soil sensor can distinguish the difference between the different pathways nor can any conventional in situ soil sensor distinguish the difference between sodium chloride and any other number of solutes that all have different electrical conductivities

5.3.2 Solution Chemistry

Salinity refers to the presence of dissolved inorganic ions such as Mg^{+} , Ca^{++}, K^{+}, Na^{+}, Cl^{-}, $SO^{2}_{4}{}^{-}$, HCO_3^{-} and CO_3^{2-} in the aqueous soil matrix (Hamed 2003) . The salinity is quantified as the total concentration of soluble salts and is expressed in terms of electrical conductivity. There exists no in-situ salinity probe that can distinguish between the different ions that may be present.

When salts such as sodium chloride are in their solid form, they exist as crystals. Within the salt crystal, the sodium and the chorine atoms are joined together in what is called an ionic chemical bond. An ionic chemical bond holds the atoms tightly together because the sodium atom will give up an electron to the chlorine thus ionizing the atoms. If an atom like sodium gives up an electron, it is said to be a positively charged ion (also called a cation). If an atom such as chlorine receives an electron, it is said to be a negatively charged ion (also called an anion and is given the suffix ide, like chloride). The sodium and the chloride ions comfortably arrange themselves into a stacked like configuration called a crystal lattice. The sodium chloride crystal lattice has a zero net charge.

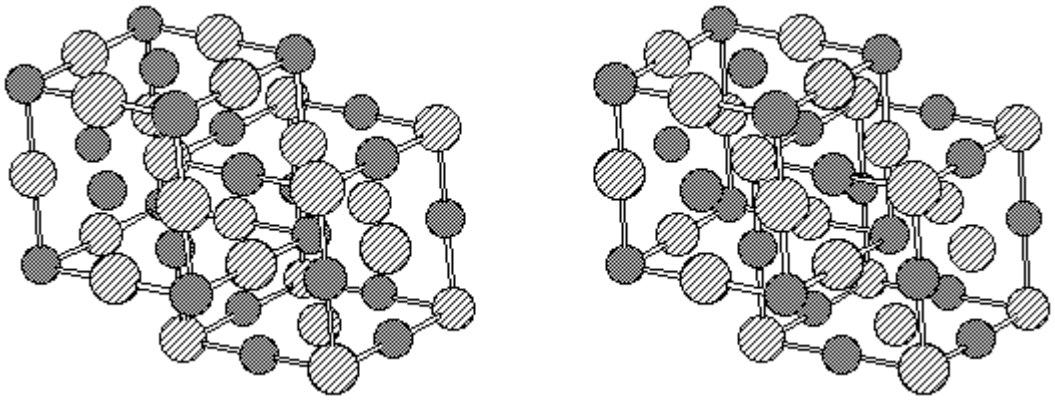

Figure [5.3] The crystal lattice model of sodium chloride. The larger spheres are chloride anions.

Water will dissolve the sodium chloride crystal lattice and physically separate the two ions. Once in solution, the sodium ion and the chloride ion will float around in the solution separately and randomly.

This is generally true for all inorganic salts. Once in a solution, the ions will float apart and become two separate species dissolved in the water. Typical, charged ions exist separately in a solution. If the water dries up, the cations and the anions will find each other and fuse back into a crystal lattice with a zero net charge.

5.3.3 Cation Exchange and Agriculture – Reclaiming Salt Infested Land

In situ soil electrical conductivity monitoring is very important in agriculture because the salinity levels in soil moisture can have dramatic effects on crop health and yields.

Agricultural soils over time may become sodic or saline and this may dramatically effect the health and yields of the crops. There are techniques that can remove the sodium to improve soil quality and increase crop production. The Stevens Hydra Probe can be an invaluable tool for monitoring the progress of saline soil reclamation.

The outer portion of a soil particle is typically negatively charged. Positively charged sodium ions will bind or “hook” onto the surface of the soil micro particle. The opposite charges create

an electronic attraction between the sodium ion and the soil. The sodium ions compete for negatively charged sites on the soil particle surface and in doing so, disperse the aggregates of soil. The aggregate dispersion of the soil caused by the sodium ions will decrease the porosity of the soil. As porosity decreases, the water holding capacity of the soil decreases. Not only are high levels of sodium ions toxic to the crops, it decreases the water that would be available to the plants.

Ion exchange reactions are the basis behind the soil reclamation practices. Saline soil reclamation includes the application of calcium rich material (such as lime or gypsum) onto the salt affected land. After application of this material, the saline affected area should be irrigated (with low saline water) to translocate the calcium down into the different horizons (layers) of soil. Once calcium ions are introduced into the horizons of the soil, the ion exchange begins.

The calcium ion has a 2+ charge where the sodium ion has a 1+ charge. Because the calcium ion has a greater electric charge, the soil will have a stronger affinity for the calcium ions than the sodium ions. The sodium is then exchanged with calcium on the soil anionic sites.

Once the calcium becomes the dominant ion present, the porosity of the soil will increase. This will be evident in the Hydra Probe soil moisture data. As the porosity increases the hydraulic conductivity will increase. The user will notice trends in the wetting fronts such as higher soil moisture values after irrigation, quick decreases to field capacity and shorter time intervals from one probe to the next as the water percolates downward.

With calcium as the dominant ion present, irrigation continues, leaching the calcium out of the soil. Calcium is less soluble than sodium, and will fall out of solution at some depth below the root zone. The removal of the calcium will be apparent in the Hydra Probe data by the decrease in electrical conductivity. The decrease in electrical conductivity will start at the Hydra Probe that is the closest to the surface, as the calcium leaches downward. Once the electrical conductivity below the root zone reaches an acceptable level, the soil can then be cultivated.

6 Maintenance and Trouble Shooting

If a probe appears to be malfunctioning, there are generally three main reasons that may explain why a probe may appear to be malfunctioning. The three most common reasons why a probe may seam to be malfunctioning are:

1) Improper logger setup or improper wiring,
2) soil hydrology may produce some unexpected results, and
3) the probe is defective.

6.1 How to tell if the Hydra Probe is Defective

The Hydra Probe goes through several tiers of quality control testing at various stages of production; therefore, it is extremely uncommon for a user to encounter a bad probe. Also, the probes are rugged enough to function for many years buried in soil.
The Hydra Probe is a dielectric constant sensor, therefore if the Hydra Probe is placed in material with a know dielectric constant, the Hydra Probe's dielectric constant measurements should match that of the literature values. Distilled water has a dielectric constant of about 80. The Hydra Probe when placed in distilled water should have a real dielectric constant (temperature corrected) from 75 to 85 and the imaginary dielectric constant should be less than 5. The Hydra Probe temperature measurement can be verified with a thermometer. Use a clean plastic container and make sure the probe is completely submerged.

All configurations of the Hydra Probe should have a real dielectric constant of about 80 in water. For special instructions for trouble shooting Analog probes see Section 2.2.3.

If the Hydra Probe produces a temperature corrected real dielectric constant of 80 +/-5 in distilled water, the Hydra Probe is NOT malfunctioning.

If distilled water is not available, the user may use tap water for this procedure. It is important to note, however, that tap water may contain trace levels of material that may affect the dielectric constants.

6.1.1 SDI-12 Hydra Probe Trouble shooting commands

To verify that the Hydra Probe is functioning properly perform the following commands: Place the Hydra Probe in distilled water in a plastic container. Make sure the entire probe is submerged. In transparent mode and with the third parameter set (aM3!), type "**1M3!**" followed by "**1D0!**" (with a probe address of 1 for this example). The typical response of a Hydra Probe that is functioning properly should be *1+77.895+78.826+2.462*. From this example, the real dielectric constant is 77.895, the temperature corrected dielectric constant is 78.826, and the imaginary dielectric constant is 2.462. According to factory specifications, the temperature corrected dielectric constant should be from 75 to 85 and the imaginary dielectric constant should be less than 5. After the probe verification, the user may wish to reset the probe back to the default parameter set or any other parameter set.

6.2 Check the Wiring

If the user is unable to get a response from the Hydra Probe it is recommended to first physically check wire connections from the probe to the logger. Check the cable for cuts and abrasions.

6.3 Logger Setup

If the connections are sound, the user will need to check the logger's setup. Programming a data logger is not a trivial task. The data logger needs to extract the data from data ports on the logger with the desired timing interval. The logger is often times the power source for the probes. The user may also want to cycle the power to the probe by disconnecting and reconnecting power. *Are the data ports enabled? Are the data ports scaled properly in the appropriate units? Are the probes and logger adequately powered? Is the data properly reported and archived on the logger's firmware?* If the logger has GUI based operation software, there may be a help function. If the logger only accepts terminal command scripts in a terminal window, refer to the logger's manual or manufacturer. Also, make sure the computer is properly connected to the logger. *Is the computer on the proper COM port? What about the Baud rate? Does the logger need a NUL modem or optical isolator in order to be connected to a computer?* Most of the technical support questions Stevens receives are not due to malfunctioning probes but rather an incorrect data logger setup.

DOTSet is a Windows program used to program a Stevens DOT Logger. Please refer to Appendix C for more information about programming DOT Loggers.

6.4 Soil Hydrology

Sometimes the soil moisture data may look incorrect when in fact the Hydra Probes are accurately measuring the actual soil moisture gradient. Soil Hydrology is complex and can be modeled by Darcy's Law and Richard's Equation. These involved theories are beyond the scope of this manual; however, knowledge of basic soil hydrology is worth discussing.

It's important to note that the soil that resides between the tine assembly is where the measurements are taken. If there is a void space in the soil between the tines, this will affect the hydrology where the Hydra Probe is taking measurements. If the void space is saturated with water, it will increase the soil moisture measurement. If the void space is not fully saturated, the soil will appear dryer. Figure 6.1 shows the measurement volume where the Hydra Probe takes measurements and a void space between the tine assembly. These void spaces can occur from a poor installation, such as rocking the probe side to side or not fully inserting the probe into the soil.

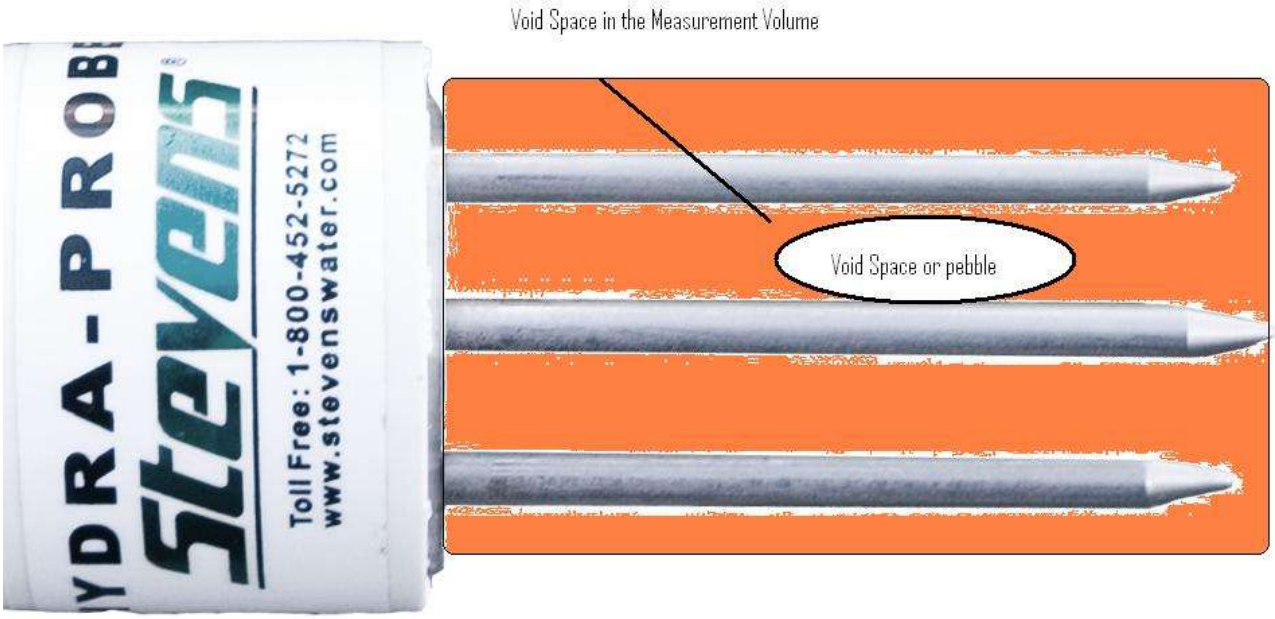

Figure 6.1 Measurement volume with a void space between the tine assembly.

Void spaces between the tine assembly can also occur from changing soil conditions. Factors such as shrink/swell clays, tree roots or pebbles may introduce a void space. The following sections describe some of these factors.

6.4.1 Evapotranspiration

Water in the soil will be pulled downward by gravity, however during dry period or in arid regions, the net movement of water is up toward the surface. Water will move upward in the soil column by a phenomenon called Evapotranspiration (ET). ET is the direct evaporation out the soil plus the amount of water being pulled out of the soil by plants. Factors such as wind, temperature, humidity, solar radiation and soil type play a role in the rate of ET. If ET exceeds precipitation, there will likely be a net upward movement of water in the soil.

6.4.2 Hydrology and Soil Texture

Sandy soils drain better than soils that are clay rich. In general, the smaller the soil particle size distribution, the slower it will drain. Sometimes silt may have the same particle size distribution, as clay but clay will retain more water for longer periods of time than silt. This can be explained by the shape of the soil particles. Clay particles are planar where as silt particles are spherical. Water basically gets stuck between the planar plate shaped clay particles and thus slows the flow of water.

6.4.3 Soil Bulk Density

In general, the greater the soil density, the less water it will hold and the slower water will move through it. There will often times be soil horizons that will be more dense than others giving the soil different hydrological properties with depth. Occasionally, water will stop or slow down and rest on a dense, less permeable layer of soil. This phenomenon is called perched water. If two Hydra Probes 20 cm apart have very different soil moisture readings, chances are that one of the probes is residing in perched water.

6.4.4 Shrink/Swell Clays

Shrink/swell clays belong to the soil taxonomic order vertisol and are composed of smectite clays. These clays have a large ion exchange capacity and will shrink and swell seasonally with water content. The seasonal expansion and contraction homogenizes the top soil and the subsoil. As the clay shrinks during a drying period, the soil will crack open and form large crevasses or fissures. If a fissure forms in the measurement volume of the Hydra Probe, the probe will signal average the fissure and potentially generate biased results. If the fissure fills with water, the soil moisture measurement will be high, if the fissure is dry, the soil moisture measurement will be lower than expected. If the Hydra Probe measurements are being affected by shrink/swell clays, It recommend to relocate the probe to an adjacent location.

6.4.5 Rock and Pebbles

Often times, it will be obvious if a rock is encountered during an installation. Never use excessive force to insert the probe into the soil. Some soils will have a distribution of pebbles. If a pebble finds its way between the probe's tines, it will create an area in the measurement volume that will not contain water. The probe will signal average the pebble and thus lower the soil moisture measurement. If the pebble is an anomaly, relocating of the probe would provide more representative soil measurements. However, if it is revealed from the soil survey that there exists a random distribution of pebbles, a pebble between the tines may provide realistic measurements because of the way pebbles influence soil hydrology.

6.4.6 Bioturbation

Organisms such as plants and burrowing animals can homogenize soil and dislodge soil probes. A tree root can grow between the tines affecting the measurements and in some cases, tree roots can bring a buried soil probe to the soil surface. Burrowing mammals and invertebrates may decide that the Hydra Probes' tine assembly makes an excellent home. If the Hydra Probe's tine assembly becomes home to some organism, the soil moisture measurements will be affected. After the animal vacates, the soil will equilibrate and the soil measurements will return to representative values.

The cable leading to the probe may also become a tasty treat for some animals. If communication between the logger and the probe fails, check the cable for damage. A metal conduit like the one shown in figure 3.7 is recommended.

6.4.7 Salt Affected Soil

The Hydra Probe is less affected by salts than TDR or other FDR soil sensors because of the operational frequency of 50Mhz. While the Hydra Probe performs relatively well in salt affected soils, salts that are dissolved in the soil water will influence both dielectric constants and thus the measurements. The salt content will increase the imaginary dielectric constant and thus the soil electrical conductivity. See Chapter 5. The Hydra Probe will not measure electrical conductivity beyond 1.5 S/m

In general, if the electrical conductivity reaches 1 S/m, the soil moisture measurements will be significantly affected. The imaginary dielectric constant will have an influence on the real dielectric constant because dissolve cations will inhibit the orientation polarization of water. When addressing the Hydra Probes' performance in salt affected soil, it is useful to use the loss tangent equation [6.1].

$$\text{Tan } \delta = E_i/E_r \qquad [6.1]$$

The loss tangent (Tan δ) is simply the imaginary dielectric constant divided by the real dielectric constant. If Tan δ become greater than 1.5 than the Hydra Probes calibration becomes unreliable. It is interesting to note that the Hydra Probe will still provide accurate dielectric constant measurements up to 1.5 S/m. If the salt content reaches a point where it is affecting the calibrations, the user can use a custom calibration that will still provide realistic soil moisture measurements in the most salt affected soils. See section 2.3 for custom calibrations.

Appendix A - SDI-12 Communication

SDI-12 (serial data interface at 1200 baud) communications protocol allows compatible devices to communicate with each other. More information about SDI-12 can be found at http://www.sdi-12.org/.

SDI-12 Wiring Information
The SDI-12 Hydra Probe has three wires. A ground wire, a +12 volt power wire and a blue data wire. The data wires from multiple probes can be connected in parallel to a terminal assembly. A single data wire from the terminal assembly can then be connected to the SDI-12 data port on the logger.

Power Requirements	9 to 20 VDC (12VDC Ideal)
Red Wire	+Volts Power Input
Black Wire	Ground
Blue Wire	SDI-12 Data Signal
Baud Rate	1200
Power Consumption	<1 mA Idle 30 mA Active

Table 2.2 Digital SDI-12 Hydra Probe II Information.

Addressing an SDI-12 Sensor
Data is communicated digitally between the probe and the logger on the single data wire. Communications over this single wire is necessarily half duplex. That is, only one device can send data at a time. SDI-12 communications is of the master/slave variety. The logger is the master and all of the probes are slaves. The probes must each have a unique address. This must necessarily be set before the probes are all connected. The probes reply with information only when they have received a valid command that is addressed to them.

It is important to note that each SDI-12 sensor must have its own unique address. If two sensors on a logger have the same address, it will disrupt communication between the loggers and the probes. The default address for the Hydra Probe is "0". The user must change the address of the probe from 0 to another letter or digit as the probes are added to the terminal assembly. The data logger's "Transparent Mode" can be used to set this address.

Changing SDI-12 Parameter Sets
In Transparent Mode, the parameter set can be changed to an alternate parameter set or set to any parameter set the user wants. For the example below, the address of the probe is 1.

A) Type "**1M!**" . the response should be ***10029***. This means that a sensor with an address of 1 will take 2 seconds to return 9 parameters with one or more D commands.

B) Type "**1XM!**". The response should be ***1HJFGOKMLN***. This means that the sensor with address 1 has been set to the first default Parameter set. The letters correspond to parameters that the Hydra Probe is capable of measuring in this set. Most users are only interested in H, J, F, and G. If the probe has another parameter set, you may wish reset the probe to the first parameter set by typing "**1M!**" or the user may type

"**1XM=GH!'** to only measure soil moisture and temperature. If the user wishes to display only the 5 raw voltages, type "**1M4!".**

Stevens Hydra Probe SDI-12 Command Specification
For Firmware Versions 2.7 and Later
The Stevens HP2 is fully compliant with the SDI-12 Version 1.2 command specification. As such, responses to many of the standard commands are not detailed here.

A complete description of the SDI-12 Command Grammar is contained in the SDI-12 Protocol Specification. This document is available online from the SDI-12 Support Group website:

http://www.sdi-12.org/

Measurement Commands

The HP2 can return any of 22 values, or parameters, as they are called in SDI-12 terminology. The following table lists the values and letter used to refer to them:

SDI-12 Parameters		
Selector	**Description**	**Units**
A	Voltage 1	Volts
B	Voltage 2	Volts
C	Voltage 3	Volts
D	Voltage 4	Volts
E	Voltage 5	Volts
F	Soil Temperature	Celsius
G	Soil Temperature	Fahrenheit
H	Soil Moisture	Percentage
I	Soil Salinity	Grams NaCl / Liter
J	Soil Conductivity (temp. corrected)	Siemens / Meter
K	Real dielectric constant	-
L	Real dielectric constant (temp. corrected)	-
M	Imaginary dielectric constant	-
N	Imaginary dielectric constant (temp. corrected)	-
O	Soil Conductivity	Siemens / Meter
P	Diode temperature	Celsius
Q	Soil Water Conductivity (temp. corrected)	Siemens / Meter
R	ADC Reading 1	-
S	ADC Reading 2	-
T	ADC Reading 3	-
U	ADC Reading 4	-
V	ADC Reading 5	-

Table 1 – Parameter Selectors

The HP2 responds to the start measurement command aM!, as well as 5 additional measurement commands, aM1! - aM5!. Each measurement command responds with a different subset of the total parameter set. The start measurement command, aM!, returns a set of readings that is user-configurable through the use of SDI-12 extended commands. This feature allows any of the 22 parameters to be accessed by older SDI-12 loggers, many of which do not support more than one measurement command. Instructions for configuring this reading set can be found in the *Extended Commands* section of this appendix.

The following measurement set descriptions detail the parameters returned by each of the measurement commands. For the aM! command, only the default reading set is listed.

All data transmitted using SDI-12 must be printable ASCII characters. The first character of any command or response is the address. The lowercase 'a' at the beginning of each command represents the address character.

SDI-12 Measurement Sets									
Command	**Response Parameters – Refer to Table 1**								
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**
aM!	H	J	F	G	O	K	M	L	N
aM1!	F	G							
aM2!	F	G	H	O	J				
aM3!	K	L	M	N	O	P	Q		
aM4!	A	B	C	D	E				
aM5!	R	S	T	U	V				

Table 2 – Measurement Command Sets

SDI-12 Extended Command Summary

The HP2 implements a number of SDI-12 extended commands. The following table lists all of the supported extended commands and a brief description:

SDI-12 Extended Commands	
Command	**Description**
aXS!	Get soil type
aXS<soil>!	Set soil type
aXP0!	Turn on the probe circuitry
aXP1!	Turn off the probe circuitry
aXM!	Get the default measure set
aXM=0!	Set the default measure set to set 0
aXM=1!	Set the default measure set to set 1
aXM=2!	Set the default measure set to set 2
aXM=3!	Set the default measure set to set 3
aXM=4!	Set the default measure set to set 4
aXM=5!	Set the default measure set to set 5
aXM=<set>!	Set custom default measure set
aXR!	Reset probe to defaults
aXY<constant>!	Get water constant
aXY<constant><float>!	Set water constant
aXW!	Get probe warmup time
aXW<warmup>!	Set probe warmup time

Table 3 – SDI-12 Extended Commands

<soil> Single ASCII character representing the soil type. The default soil type is *4*.

Values:
- 1 Sand
- 2 Silt
- 3 Clay
- 4 Loam
- C Custom 1
- D Custom 2

<set> String of 1-9 ASCII characters that specify the measurements taken by the standard measurement command (aM!). Valid values are any of the letters A-V. The default measurement set is *HJFGOKMLN*.

<constant> Single ASCII character specifying the water constant accessed by the command. Water constants are used in conjunction with the *Custom* soil types. When a *Custom* soil type is selected, the probe will use the water constants to compute the soil moisture content. Custom 1 uses all 4

constants, Custom 2 uses the first 2 constants only. The default constant values are the same as the *Silt* soil type.

Values:

A	Constant A
B	Constant B
C	Constant C
D	Constant D

<float> Decimal number, optionally using a form of scientific notation.
Ex: "+23.54, 0.001, -123.0E5, 45.E-3"

<warmup> 16-bit integer value between 0-65535. This is the number of milliseconds that the probe is enabled before measurements are taken and ready. The default value is *1000*.

<id-string> Identification string containing the manufacturer, model number, version and manufacturer specific data. In this case the specific data is the soil type and serial number. Example:

012STEVENSW0000012.7ST4SN00000000

SDI-12 Extended Command Descriptions

aXS! – Get soil type

Returns the current soil type of the HP2.
Response: a<soil><CR><LF>

aXS<soil>! – Set Soil Type

Sets the soil type specified by <soil>. Returns the new soil type of the HP2.
Response: a<soil><CR><LF>

aXP0! – Turn on probe circuitry

Switches on the voltage to the HP2 RF section.
Response: aPROBE:ENABLED<CR><LF>

aXP1! – Turn off probe circuitry

Switches off the voltage to the HP2 RF sections.
Response: aPROBE:DISABLED<CR><LF>

aXM! – Get default measurement set

Returns the <set> specifying the readings returned by the aM! Command.
Response: a<set><CR><LF>

aXM=0! – Set default measurement set to measurement set 0

Sets the default measurement set to *HJFGOKMLN*.
Response: a*HJFGOKMLN* <CR><LF>

aXM=1! – Set default measurement set to measurement set 1

Sets the default measurement set to *FG*.
Response: aFG<CR><LF>

aXM=2! – Set default measurement set to measurement set 2

Sets the default measurement set to *FGHOJ*.
Response: aFGHOJ<CR><LF>

aXM=3! – Set default measurement set to measurement set 3

Sets the default measurement set to *KLMNOPQ*.
Response: aKLMNOPQ<CR><LF>

aXM=4! – Set default measurement set to measurement set 4
Sets the default measurement set to *ABCDE*.
Response: aABCDE<CR><LF>

aXM=5! – Set default measurement set to measurement set 5
Sets the default measurement set to *RSTUV*.
Response: aRSTUV<CR><LF>

aXM=<set>! – Set custom default measurement set
Set the default measurement set to a custom <set>. Returns the new default measurement set.
Response: a<set><CR><LF>

aXR! – Reset probe to defaults
Resets all probe settings to default.
Response: a<id-string><CR><LF>

aXY<constant>! – Get water constant
Returns the water constant specified by <constant>.
Response: a<float><CR><LF>

aXY<constant><float>! – Set water constant
Sets the water constant specified by <constant> with the specified <float> value. Returns the new <float> value of the specified water constant.
Response: a<float><CR><LF>

aXW! – Get probe warmup time
Returns the warmup time used by the HP2 before taking a measurement.
Response: a<warmup><CR><LF>

aXW<warmup>! – Set probe warmup time
Sets the warmup time specified by <warmup>. Returns the new warmup time.
Response: a<warmup><CR><LF>

Appendix B - RS-485 Communication

The RS-485 Hydra Probe is also digital and uses an RS-485 communication format. The RS-485 Hydra Probe has 4 wires: a ground wire, a +12 volt power wire and 2 data wires. The RS-485 Hydra Probe communicates through two data wires and can be wired into a RS-485 port on a logger. They can be connected to a terminal assembly like the SDI-12 version, but with four wires instead of three. The advantage RS-485 has over the SDI-12 version is that the RS-485 version's cable can run over 3000 feet. The disadvantage is that it draws more power.

Power Requirements	9 to 20 VDC (12VDC Ideal)
Red Wire	+Volts Power Input
Black Wire	Ground
White Wire	Data Signal A non-inverting signal
Green Wire	Data Signal B inverting signal
Baud Rate	9600 8N1
Power Consumption	<10 mA Idle 30 mA Active

Table 2.3 Digital RS-485 Hydra Probe II Information.

Stevens Hydra Probe RS-485 Command Specification
For Use with Firmware Version 2.7 and Later

Command Format

```
AAACC<CR><LF>           Execute
AAACC=?<CR><LF>         Query current setting
AAACC=XXX…<CR><LF>      Assign new value

AAA:        3 byte address
            ASCII characters, 0-9 A-Z a-z
            Wildcard character: "/"
            Broadcast address: "///"

CC:         2 byte command

XXX…:       Command data.  See command info for specific requirements.

<CR>:       Carriage return character (ASCII 13)

<LF>:       Linefeed character (ASCII 10)
```

Other Grammar

```
<d>:        Digit, ASCII '0' through ASCII '9'

<a>:        ASCII 'A' through ASCII 'D', used for custom water constant

<serial>:   Serial number, 8 digits. <d><d><d><d><d><d><d><d>

<soil>:     Soil Type, 1 character {'1' | '2' | '3' | '4'| 'C' | 'D'}
```

<quick>: Quick mode, 1 character {'1' – '6', 'X'}

<warmup>: Warmup time, 1-5 digits, 0-65535

<bool>: Boolean value, 1 character, {'0' | '1'}

<firmware>: Firmware, 3 or 4 bytes, formatted like "2.7" or "R2.7" or "2s7"

<text>: Printable ASCII text

<float>: Decimal number, optionally using a form of scientific notation. Ex: "+23.54, 0.001, -123.0E5, 45.E-3"

<readings>: Comma-delimited string of floats. Ex: "+23.54,-42.532,+2342.12"

Hydra Probe Specific RS-485 Commands

Information Commands

Serial Number

Description:	Returns the factory serial number.
Access Level:	Read only
Read Addresses:	Broadcast, Exact
Read Command:	<addr>SN=?<CR><LF>
Read Response:	<addr><serial><CR><LF>

Firmware Version

Description:	Returns the firmware version number.
Access Level:	Read only
Read Addresses:	Broadcast, Exact
Read Command:	<addr>FV=?<CR><LF>
Read Response:	<addr><firmware><CR><LF>

Standard Configuration Commands

Address

Description:	Gets/sets the probe address.
Access Level:	Read/Write
Read Addresses:	Broadcast, Exact
Read Command:	<addr>AD=?<CR><LF>
Read Response:	<addr><CR><LF>
Write Addresses:	Exact
Write Command:	<addr>AD=<serial><new_addr><CR><LF>
Write Response:	<new_addr><CR><LF>

Soil Type

Description:	Gets/sets the probe soil type.
Access Level:	Read/Write
Read Addresses:	Broadcast, Exact
Read Command:	`<addr>ST=?<CR><LF>`
Read Response:	`<addr><CR><LF>`
Write Addresses:	Broadcast, Exact, Wildcard
Write Command:	`<addr>ST=<soil><CR><LF>`
Write Response:	`<addr><soil><CR><LF>` (No response for wildcard address)

Advanced Configuration Commands

Location

Description:	Gets/sets the probe location.
Access Level:	Read/Write
Read Addresses:	Broadcast, Exact
Read Command:	`<addr>LO=?<CR><LF>`
Read Response:	`<addr><text><CR><LF>`
Write Addresses:	Exact
Write Command:	`<addr>LO=<text><CR><LF>`
Write Response:	`<addr><text><CR><LF>`

Description

Description:	Gets/sets the probe description.
Access Level:	Read/Write
Read Addresses:	Broadcast, Exact
Read Command:	`<addr>DS=?<CR><LF>`
Read Response:	`<addr><text><CR><LF>`
Write Addresses:	Exact
Write Command:	`<addr>DS=<text><CR><LF>`
Write Response:	`<addr><text><CR><LF>`

Custom Water Constants

Description:	Gets/sets the custom probe water constants.
Access Level:	Read/Write
Read Addresses:	Broadcast, Exact
Read Command:	`<addr>X<a>=?<CR><LF>`
Read Response:	`<addr><float><CR><LF>`
Write Addresses:	Exact
Write Command:	`<addr>X<a>=<float><CR><LF>`
Write Response:	`<addr><float><CR><LF>`

Quick Mode

Description:	Gets/sets the probe quick reading response mode.
Access Level:	Read/Write
Read Addresses:	Broadcast, Exact
Read Command:	`<addr>QM=?<CR><LF>`
Read Response:	`<addr><quick><CR><LF>`
Write Addresses:	Exact
Write Command:	`<addr>QM=<quick><CR><LF>`
Write Response:	`<addr><quick><CR><LF>`

Debug Commands

Warmup Time

Description:	Gets/sets the custom probe warmup time.
Access Level:	Read/Write
Read Addresses:	Broadcast, Exact
Read Command:	`<addr>WT=?<CR><LF>`
Read Response:	`<addr><warmup><CR><LF>`
Write Addresses:	Exact
Write Command:	`<addr>WT=<warmup><CR><LF>`
Write Response:	`<addr><warmup><CR><LF>`

Probe Enable

Description:	Gets/sets whether the probe circuitry is enabled.
Access Level:	Read/Write
Read Addresses:	Broadcast, Exact
Read Command:	`<addr>PE=?<CR><LF>`
Read Response:	`<addr><bool><CR><LF>`
Write Addresses:	Exact
Write Command:	`<addr>PE=<bool><CR><LF>`
Write Response:	`<addr><bool><CR><LF>`

Measurement Commands

Take Reading

Description:	Instructs a probe or group of probes to take a reading sample.
Access Level:	Execute
Execute Addresses:	Broadcast, Exact, Wildcard
Execute Command:	`<addr>TR<CR><LF>`
Execute Response:	`(none)`

Transmit Reading Set

Description:	Instructs a probe to transmit a specific reading set.
Access Level:	Execute
Execute Addresses:	Broadcast, Exact
Execute Command:	`<addr>T<set><CR><LF>`
Execute Response:	`<addr><readings><CR><LF>`

RS-485 TRANSMIT SETS

(tc) indicates values that have been temperature corrected

T0 - Transmit Set 0:
- H) Moisture
- J) Conductivity (tc)
- F) Temp C
- G) Temp F
- O) Conductivity
- K) Real Dielectric
- M) Imag Dielectric
- L) Real Dielectric (tc)
- N) Imag Dielectric (tc)

T1 - Transmit Set 1:
- F) Temp C
- G) Temp F

T2 - Transmit Set 2:
- F) Temp C
- G) Temp F
- H) Moisture
- O) Conductivity
- J) Conductivity (tc)

T3 - Transmit Set 3:
- F) Temp C
- G) Temp F
- H) Moisture
- I) Salinity
- J) Soil Conductivity (tc)
- K) Real Dielectric
- L) Real Dielectric (tc)
- M) Imag Dielectric
- N) Imag Dielectric (tc)
- O) Soil Conductivity
- P) Diode Temperature
- Q) Water Conductivity (tc)

T4 - Transmit Set 4:
- A) V1 (volts)
- B) V2 (volts)
- C) V3 (volts)
- D) V4 (volts)
- E) V5 (millivolts)

T5 - Transmit Set 5:
- R) V1 raw adc
- S) V2 raw adc
- T) V3 raw adc
- U) V4 raw adc
- V) V5 raw adc

Appendix C - Stevens DOT Logger with the SDI-12 Hydra Probe

The Stevens DOT Logger is the perfect companion for the Hydra Probe. The DOT logger has 100 SDI-12 channels for recording data. For example, 33 Hydra Probes each measuring 3 parameters such as EC, temperature and soil moisture, can be connected to a single DOT logger. (100 available SDI-12 channels divided by 3 parameters per sensor = a rounded 33 sensors).

Tutorial

The following tutorial will show how to program the DOT Logger with two SDI-12 Hydra Probes. The two Hydra Probes will need to be programmed to measure soil moisture, temperature in Celsius and soil electrical conductivity. The DOT Logger will need to be programmed to take measurements every hour and the user will need to store the data in a file that can be used with Excel, a spreadsheet program from Microsoft.

Step 1 - Connect the DOT Logger to a PC

Power the DOT Logger with a +12 Volt power source and ground. Connect the DOT Logger to a PC that has DOTset software loaded. DOTset comes with the DOT Logger or can be downloaded for free at Stevenwater.com. Connect the DOT Logger to the PC with an RS-232 serial cable.

Step 2 - Connect one of the Hydra Probes to the Terminal assembly

Connect one of the Probes to a terminal assembly, and connect the terminal assembly data wire into the SDI-12 Port on the DOT Logger. The +12 volt and ground connection points on the DOT Logger can be used to power a small number of sensors.

Step 3 - Address the SDI-12 Probes

Each SDI-12 Probe needs to have its own unique address or there will be communication conflict on the logger. All of Hydra Probes leave the factory with an address of 0. The address of one of the probes must be changed before wiring the second probe into the terminal assembly.

A) Open the DOTset Software and click the connect button. A Green light will appear when the logger is connected
B) Open the SDI-12 Window by clicking on SDI-12 on the left side of the DOTset window.
C) Click the Transparent Mode Box. The Transparent Mode Window should pop up and ask for a sensor command. Have **`CAP LOCK`** enabled.
D) Type **`?!`** in the command box that is located below the Response box in the Transparent Mode Window. The **`?!`** Command asks the sensor for its address.
   The response from the sensor in the response box should be:

```
Enter Sensor Command: ?!
Response from sensor: 0
```

   The address of this sensor is "**`0`**" and it needs to be changed before the other sensor can be added.

E) Type: **`0A1!`** This command changes the address from **`0`** to **`1`**. The response in the response box should be:

Enter Sensor Command: 0a1!
Response from sensor: 1!

If in doubt, type **?!** to verify the address change.

F) While in Transparent Mode, the user may wish to confirm the parameter set. Type **1XM!** The response should be:

Enter Sensor Command: 1XM!
Response from sensor: 1HJFGOKMLN

This means that a probe with an address of **1** is set for the default parameter set. See Table 2 in Appendix A for definitions. In this example we are only interested in **HJF** which are parameters 1, 2 & 3 which correspond to soil moisture, temperature in Celsius and soil electrical conductivity. Leave Transparant Mode. For this example we will assume that the second probe has an address of **0** and has the same default parameter set.

G) Connect both Hydra Probes to the terminal assembly.

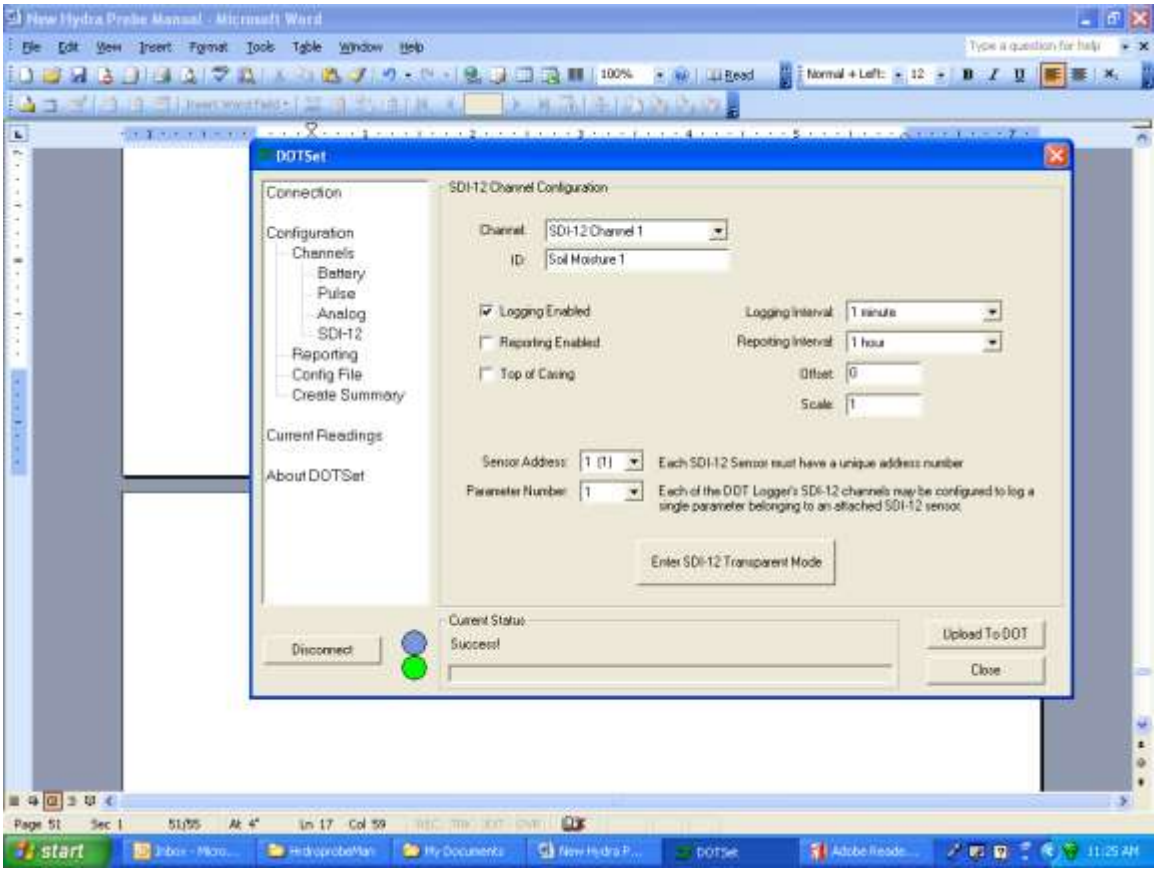

Figure C1 DOTset

Step 4 Setting the SDI-12 Channels

On the DOT logger, everything is recorded on a channel basis. Each parameter is recorded on its' own channel. For every parameter that you wish to record, a channel will need to be assigned and then configured for that use. In the SDI-12 window of DOTset, the SDI-12 channels can be set up. In this example, we will need to set up 6 channels. Table C.1 shows the channel set up for

this example. Note that for compatibility with Logger XL, channel ID names must be no more than six characters long and cannot contain any spaces. In this table "Soil Moisture" has been abreviated "SM", "Electrical Conductivity" has been abreviated "EC" and "Temperature" has been abreviated "Temp".

SDI-12 Channel	Sensor Address	Sensor Parameter	ID	Logging Interval
Channel l	0	1	SM0	1 hour
Channel 2	0	2	EC0	1 hour
Channel 3	0	3	Temp0	1 hour
Channel 4	1	1	SM1	1 hour
Channel 5	1	2	EC1	1 hour
Channel 6	1	3	Temp1	1 hour

Table C.1 Tutorial SDI-12 Channel setup. Sensor parameters 1, 2 & 3 correspond to parameters HJF in Table 2 in Appendix A.

Each channel now needs to be programmed with the information from this table. The user can switch channels by clicking on the channel field toward the top of the DOTset window. Below are the programmable options for each channel.

Channel: The user can switch channels
ID: The user can name the channel
Logging Enabled: Check this box to enable logging
Reporting Enable: Check this box if you have telemetry
Top of Casing: Offset for water level probes
Logging interval: The User can select a logging interval
Reporting Interval: Reports to Radio or Modem
Offset: Offset, added to reading.
Scale: Multiplier.
Sensor address: Sets Sensor address
Sensor Parameter: Sets Sensor Parameter.

For the Hydra Probe, TOC, Offset and Scale can be left at their default settings. That is TOC should not be checked, Offset should be zero, and Scale should be 1.

Step 5 Click "Upload to DOT" to load all of the channel configurations to the DOT Logger. The DOT Logger is now logging. Close DOTset.

Steps 1 though 5 set up the data logger and the probes. Once logging is enabled, the system will start taking measurements and start logging data.

Step 6 Retrieving Data.
To retrieve the data, launch "Stevens Logger XL".

Step 7 Set up Logger XL.

- From the main window select "Define DOT logger batch".

- Check the “Access Dot Logger batch” box.
- Select “All channels” in the Batch list Dialog box.

Next, go to the configuration menu, data access setting and:

- check “auto create data.csv.file”
- check “append data to file”.

Under configurations, comport settings:

- select COM1,
- Echo off,
- Parity none,
- Stop bits 1,
- Data bits 8
- Flow control Xon/Xoff.

Step 8 Click on the black box in the upper right side of the terminal window and a smiley face should appear. Logger XL is connected to the logger when

Welcome
1.N

appears in the window.

Step 9 Click the D box at the top of the screen. This opens the Data Dump Window.

1.N
> 12.0 VDC
> DOT Logger Commlink Found

should appear in the window.

Step 10 Depending on your computer operating system, the data should automatically start to download. The data is down loading when dots start appearing in the data. If it doesn’t start down loading on its own, click the DOT Link button

Step 11 When the data is done down loading. “**Down Load Complete**” will appear in the Data Dump window. The data will be in a file titled with the date of down load in:

Program Files/Axread.

Appendix D - Statistics

All measurements, no matter how careful and scientific, are subject to some uncertainties. Statistics is the branch of mathematics that can quantify uncertainties. The Hydra Probe's design and signal processing reduces error to a magnitude that has little impact on hydrological measurements such as permanent wilting point, field capacity and saturation.

Parameter	**Accuracy/Precision**
Temperature (C)	+/- 0.6 Degrees Celsius(From -10^{o} to 36^{o}C)
Soil Moisture wfv (m^3 m^{-3})	+/- 0.03 wfv (m^3 m^{-3}) Accuracy
Soil Moisture wfv (m^3 m^{-3})	+/- 0.003 wfv (m^3 m^{-3}) Precision
Electrical Conductivity (S/m) TUC*	+/- 0.0014 S/m or +/- 1%
Electrical Conductivity (S/m) TC**	+/- 0.0014 S/m or +/- 5%
Real/Imaginary Dielectric Constant TUC*	+/- 0.5 or +/- 1%
Real/Imaginary Dielectric Constant TC*	+/- 0.5 or +/- 5%

Table 1.1 Accuracy and Precision of the Hydra Probes' Parameters.
*TUC Temperature uncorrected full scale
**TC Temperature corrected from 0 to 35^{o} C

The Hydra Probe offers better precision and accuracy than TDR and other FDR type soil probes because:

1) the signal response is ratiometric maximizing reproducibility,
2) the frequency of 50 MHz provides enough energy to achieve the molecular polarization of water while maintaining a quantifiable imaginary dielectric constant,
3) the values are temperature corrected, and
4) the calibration curves are solute independent in most soil environments and have high R^2 values.

The Hydra Probe's precision was calculated from the standard deviation. The accuracy of the soil moisture measurements were calculated from the deviation about the calibration curve. In most cases, the R^2 value for soil moisture is 0.97 to 0.99. The accuracy of the soil electrical conductivity was calculated from the standard deviation of measurements taken in conductivity standards.

Statistical Definitions

R^2 Shows how well a distribution of points fit on a straight line. The closer the R^2 value is to 1 the more correlated the data the better the accuracy.

$$R^2 = \frac{SS_R}{SS_T} = 1 - \frac{SS_E}{SS_T}.$$

In the above definition,

$$SS_T = \sum_i (y_i - \bar{y})^2, SS_R = \sum_i (\hat{y}_i - \bar{y})^2, SS_E = \sum_i (y_i - \hat{y}_i)^2.$$

The average

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{N} x_i = \frac{x_1 + x_2 + \cdots + x_N}{N}$$

The Standard deviation represents precision and reproducibility.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (x_i - \overline{x})^2}$$

Precision verses accuracy

Figure A.4.1 Good Precision Bad Accuracy

Figure A.4.2 Good Accuracy Bad Precision

Appendix E - Ordering Information

Table E.1 lists the part numbers, and some accessories such as the Stevens Dot Logger. The RS-485 Hydra Probe has a cable length limit of 1000 meters. The SDI-12 version has a limit of 50 meters, and the analog versions have a maximum cable length of 33 meters. It is difficult to go beyond the maximum recommended cable length because capacitance effects of the cable absorb the signal. The Analog, RS-485 and the SDI-12 versions are designed to be permanently (or semi permanently) buried in soil and the portable version allows the user to collect the same quality of data with hand held devices.

Part	**Stevens Part number**
Hydra Probe II Digital 25 ft Cable	93460 -025 (SDI-12 or RS485)
Hydra Probe II Digital 50 ft Cable	93460 -050 (SDI-12 or RS485)
Hydra Probe II Digital 100 ft Cable	93460 -100 (SDI-12 or RS485)
Hydra Probe II Extended Temp Range 25 ft Cable	93640-025-30 (SDI-12 or RS485)
Hydra Probe II Extended Temp Range 50 ft Cable	93640-055-30 (SDI-12 or RS485)
Hydra Probe II Extended Temp Range 100 ft Cable	93640-100-30 (SDI-12 or RS485)
Hydra Probe 1 Analog 25 ft Cable	70030-025
Hydra Probe 1 Analog 50 ft Cable	70030-050
Hydra Probe 1 Analog 100 ft Cable	70030-100
HYD JIG Installation Tool	92880
DOT Logger	93273
Hydra Data Reader	93342 (not including the probe)

Table E.1 Stevens Part numbers for available versions of the Hydra Probe and Accessories

Appendix F - Useful links

Stevens Water Monitoring Systems, Inc.
www.stevenswater.com

Soilsensor.com – Soil Monitoring Made Easy
www.soilsensor.com

The Soil Science Society of America
http://www.soils.org/

The US Department of Agriculture NRCS Soil Climate Analyses Network (SCAN)
http://www.wcc.nrcs.usda.gov/scan/

The US Department of Agriculture NRCS Snotel Network
http://www.wcc.nrcs.usda.gov/snow/

The US Geological Survey Agricultural Weather Network (AgriMet)
http://www.usbr.gov/pn/agrimet/

Free Nationwide Soil Survey Information!
http://soildatamart.nrcs.usda.gov/

Appendix G - References

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Whalley, W. R. 1993. Considerations on the use of time-domain reflectometry (TDR) for measuring soil water content. J. Soil Sci. 44:1-9.

Appendix H - WARRANTY

Stevens Water Monitoring Systems, Inc. warrants that the product you have purchased will be free from defects in material and workmanship.

This warranty covers all defects which you bring to the attention of Stevens within two years from the date of shipment.

If your Stevens product is defective, Stevens will repair or replace it and will ship it back to you free of charge.

You must return your Stevens product within two years of the ship date, shipping prepaid, to our factory at this address:

Stevens Water Monitoring Systems, Inc.
12067 NE Glenn Widing Drive, Suite 106
Portland, OR 97220
(800) 452-5272

In any correspondence with us, or if you send us part of the product but not all, please include both the model and the serial number of the product.

WHAT THIS WARRANTY DOES NOT COVER

Your rights and remedies are limited to those sent out in this warranty. Stevens Water Monitoring Systems, Inc. disclaims all implied warranties, including the warranties of merchantability and fitness for a particular purpose. Stevens shall not be liable for special, incidental or consequential damage. In no event will Stevens liability to you exceed the purchase price of your Stevens product.

For your reference, please enter the date of receipt and serial number of the instrument covered by this warranty in the space below.

Date of receipt _____ Serial number _____